# TESTING A CONCEPTUAL MODEL OF VOCAL TREMOR: RESPIRATORY AND LARYNGEAL CONTRIBUTIONS TO ACOUSTIC MODULATION

by

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ABSTRACT

Vocal tremor is a neurogenic voice disorder characterized by rhythmic modulation of pitch and loudness during sustained phonation and is acoustically measured as modulation of formants, fundamental frequency (fo), and sound pressure level (SPL). To date, links between oscillating vocal tract structures and acoustic modulation of the first two formants were shown in those with vocal tremor. However, laryngeal and respiratory contributions to acoustic modulation patterns in those with vocal tremor are difficult to separate. The purpose of this study was to compare acoustic patterns associated with volitional laryngeal versus respiratory structure oscillations in trained singers. Laryngeal oscillation was hypothesized to correspond with fo modulation patterns, whereas respiratory system oscillation was hypothesized to correspond with SPL modulation. Ten classically trained female singers with no less than 5 years' experience and no history or current complaints of voicing problems were recruited between 40–65 years of age. All participants underwent simultaneous recording of nasoendoscopic views of the larynx, respiratory kinematic and acoustic signals during three trials of sustained phonation of /i/ using either vibrato or the Accented Method of Voicing (AMV). Normalized measures of signal modulation rate and magnitude were completed on the acoustic (fo and SPL) and kinematic recordings. A mixed effects logistic regression compared within subject measurement differences between voicing conditions. The results showed significantly greater magnitude of respiratory kinematics during AMV (47.5% (+1.2)) than for vibrato (0% (+0) ($p < .001$) corresponding with significantly greater SPL modulation magnitude (AMV = 40% (+20); vibrato = (10% (+0)), respectively ($p = .026$). A significant difference was also found between voicing conditions for modulation rate of fo ($p = .049$) and SPL ($p < .001$). The rates of modulation during AMV were slower (fo = 2.8 (+ .8) Hz; SPL = 2.1 (+ .7) Hz) than for vibrato (fo = 5.1 (+ .7) Hz; SPL = 5 (+ .6) Hz). However, laryngeal kinematic and acoustic fo and SPL magnitude patterns did not differ between voicing conditions. Outcomes support predicted contributions of the respiratory system to voicing modulation; however, the larynx appears interactive with the respiratory and other speech structures during voicing.

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# INTRODUCTION

## Background

Tremor is defined as involuntary, rhythmic, oscillatory movement produced by either synchronous or alternating contractions of antagonistic muscles (e.g., the biceps and triceps) (Dalvi & Premkumar, 2011; Finnegan, Luschei, Barkmeier, & Hoffman, 2003; Schneider & Deuschl, 2015). Tremor is considered to occur related to disinhibition, excitation, or poor regulation of central nervous system oscillatory neural networks associated with neurological disorders, pharmaceutical side effects, or limbic system effects (Dalvi & Premkumar, 2011). Tremor is typically classified by its rate, the structures affected, and conditions under which it manifests (Dalvi & Premkumar, 2011).

The majority of the literature describing tremor focuses on neurological disorders involving the limbs, head, and trunk of the body. However, tremor can also involve structures associated with speaking, typically resulting in the production of a shaky voice quality referred to as, "vocal tremor." Chronic occurrence or progression of vocal tremor has been shown to significantly impact the intelligibility and quality of life of affected individuals (Louis & Machado, 2015). The resulting negative impact on quality of life may motivate them to seek remediation through pharmaceutical (Gurey, Sinclair, Blitzer, 2013; Warrick et al., 2000), behavioral (Barkmeier-Kraemer, Lato, & Wiley, 2011) or surgical management (Taha, Janszen, & Favre, 1999). Current knowledge about vocal tremor is related to its association with other neurological disorders and its acoustic patterns. The most common etiology associated with vocal tremor is Essential Tremor (ET), the most common form of movement disorder (Dalvi & Premkumar, 2011). Interestingly, 93% of those diagnosed with Essential Vocal Tremor are female (Sulica & Louis, 2010). Vocal tremor has also been identified in individuals diagnosed with other neurological disorders such as spasmodic dysphonia and Parkinson's disease (Wolraich, Marchis-Cristan, Redding, Khella, & Mirza, 2010); however, demographic comparisons of vocal tremor across the latter neurological disorders have not been completed.

A small number of studies have characterized speaking patterns associated with vocal tremor (Lundy, Roy, Xue, Casiano, & Jassir, 2004) as well as the ability to perceive vocal tremor across different speech contexts (Brown & Simonson, 1963; Lederle, Barkmeier-Kraemer, & Finnegan, 2012). Vocal tremor is best perceived during sustained phonation context (Brown & Simonson, 1963), although severe vocal tremor can also be perceived within connected speech (Lederle et al., 2012). Individuals with vocal tremor have also been shown to speak at a slower rate, on average, compared to normal speakers (Lundy et al., 2004). In general, vocal tremor is perceived as a rhythmic modulation of pitch and loudness associated with acoustic modulation of fundamental frequency ($f_o$) and sound pressure level (SPL), respectively.

Modulation of pitch and loudness associated with vocal tremor has been characterized by measuring the acoustic correlates, fundamental frequency ($f_o$) and sound pressure level (SPL), respectively. Vocal tremor modulation rate for both $f_o$ and SPL has been reported to occur between 3-8 Hz (Brown & Simonson, 1963; Dromey, Warrick, & Irish, 2002; Ramig & Shipp, 1987). The extent of $f_o$ modulation in vocal tremor has been reported to range between 3-17% with an extent of SPL modulation reported to range between 19-61% (Barkmeier-Kraemer, Lato, & Wiley, 2011; Dromey et al., 2002; Ramig & Shipp, 1987). Thus, it appears that the larger extent of acoustic modulation during vocal tremor may be due to SPL compared to $f_o$ modulation.

The majority of literature addressing vocal tremor has characterized the rate, extent, and conditions under which it is detected relying primarily on associated acoustic patterns. A small number of studies also investigated musculature or structures within the speech mechanism exhibiting tremor associated with vocal tremor. Based on prior literature identifying tremor within structures of the speech mechanism, the majority noted tremor within the pharyngeal constrictors (Sulica & Louis, 2010), larynx (Ackermann & Ziegler, 1991; Adler et al., 2004; Bové et al., 2006; Finnegan et al., 2003; Gamboa et al., 1998; Sulica & Louis, 2010; Tomoda, Shibasaki, Kuroda, & Shin, 1987), and tongue (Gamboa et al., 1998; Jiang, Lin, & Hanson, 2000; Sulica & Louis, 2010; Lester, Barkmeier-Kraemer, & Story, 2013) (see Table 1). The latter structures may be most frequently associated with vocal tremor due to their ease of observation during endoscopic evaluation. However, tremor has also been identified in other structures such as the soft palate (Sulica & Louis, 2010) and respiratory musculature (Tomoda et al., 1987). Although the majority of literature addressing vocal tremor has focused on the larynx, approximately 25% of those with vocal tremor exhibit tremor in structures outside of the larynx, or within the vocal tract (Bové et al., 2006). Although prior studies have noted tremor affecting

Table 1. Speech structures reported to exhibit tremor.

| **Study** | **Subjects** | **Methods** | **Speech Structures Studied with Tremor** |
|---|---|---|---|
| Sulica, L., & Louis, E. D. (2010). Clinical characteristics of essential voice tremor: A study of 34 cases. The Laryngoscope, 120(3), 516-528. | N=34 with ET | Vocal Tremor Scoring System (VTSS) for laryngeal and pharyngeal movement, Washington Heights Inwood Genetic Study of Essential Tremor (WHIGET) rating scale for arm tremor, Voice Handicap Index (VHI) for voice disability rating. | Larynx, Pharynx, Palate, Tongue |
| Finnegan, E. M., Luschei, E. S., Barkmeier, J. M., & Hoffman, H. T. (2003). Synchrony of laryngeal muscle activity in persons with vocal tremor. Archives of Otolaryngology–Head & Neck Surgery, 129(3), 313-318. | N=6 with VT | EMG and acoustic analysis from voice recordings | Laryngeal musculature: Cricothyroid, Thyroarytenoid, Sternohyoid, Thyrohyoid |
| Tomoda, H., Shibasaki, H., Kuroda, Y., & Shin, T. (1987). Voice tremor: Dysregulation of voluntary expiratory muscles. Neurology, 37(1), 117-122. | N=3 with Tremor in voice and hands | EMG and acoustic analysis from voice recordings | Cricothyroid (larynx), Rectus abdominis (chest wall) |
| Ackermann, H., & Ziegler, W. (1991). Cerebellar voice tremor: an acoustic analysis. Journal of Neurology, Neurosurgery & Psychiatry, 54(1), 74-76. | N=1 with Cerebellar tremor | Acoustic analysis from voice recordings | Larynx only |
| Gamboa, J., Jiménez-Jiménez, F. J., Nieto, A., Cobeta, I., Vegas, A., Ortí-Pareja, M., García-Albea, E. (1998). Acoustic voice analysis in patients with essential tremor. Journal of Voice, 12(4), 444-452. | N=56 (28 with ET; 28 control) | Acoustic analysis from voice recordings | Larynx, Vocal Tract (articulators) |
| Jiang, J., Lin, E., & Hanson, D. G. (2000). Acoustic and Airflow Spectral Analysis of Voice Tremor. Journal of Speech, Language & Hearing Research, 43(1), 191. | N=10 (5M, 5F) neuro-logical disease showing signs of VT | Acoustic analysis, airflow analysis | Vocal Tract (articulators) |

Table 1. Continued

| | | | |
|---|---|---|---|
| Lester, R. A., Barkmeier-Kraemer, J., & Story, B. H. (2013). Physiologic and Acoustic Patterns of Essential Vocal Tremor. Journal of Voice, 27(4), 422-432. | N=1 with EVT | Rigid videostroboscopy, acoustic analysis, simulation using computer model | Larynx, Vocal Tract (articulators) |
| Adler, C. H., Bansberg, S. F., Hentz, J. G., Ramig, L. O., Buder, E. H., Witt, K., Edwards, B. W., Krein-Jones, K., & Caviness, J. N., (2004). Botulinum toxin type A for treating voice tremor. Archives of Neurology, 61(9), 1416-1420. | N=13 with VT | Video laryngostroboscopy, acoustic analysis | Larynx |
| Bové, M., Daamen, N., Rosen, C., Wang, C. C., Sulica, L., & Gartner-Schmidt, J. (2006). Development and Validation of the Vocal Tremor Scoring System. The Laryngoscope, 116(9), 1662-1667. | N=10 with VT | Transnasal videostroboscopy, acoustic analysis | Larynx |

speech structures in individuals with vocal tremor, none of these studies compared the contribution of oscillating speech structures to the final acoustic output.

To better elucidate the impact of tremor on voice and speech, improved understanding of the contribution of speech structures on the associated acoustic signal needs to be prospectively studied. To date, attempts to characterize vocal tremor by neurogenic disorder has not been successful due to the range of acoustic patterns demonstrated using primarily $f_o$ and SPL rate patterns, in some cases comparing measures across pitch productions. However, literature addressing tremor in the limbs has systematically studied the rate, extent, and conditions under which tremor occurs to classify and diagnose different forms of tremor. The impact of tremor on functional movements during everyday activities is considered by neurologists to be the symptoms that bring patients to the clinic. Similarly, patients with vocal tremor complain of speech and voice problems, but analysis of the acoustic correlates of the symptoms does not provide insight into the underpinnings of vocal tremor physiology and its influence on the speech mechanism. To address the physiologic underpinnings of vocal tremor, a conceptual model was developed by Barkmeier-Kraemer and Story (2010) (see Figure 1).

The conceptual model of vocal tremor proposes that tremor oscillation originating from structures of the respiratory, phonatory, and articulatory systems will contribute hypothesized patterns of acoustic modulation during voice production (see Figure 1). For example, tremor oscillations within the respiratory system are hypothesized to result in acoustic modulation of sound pressure level

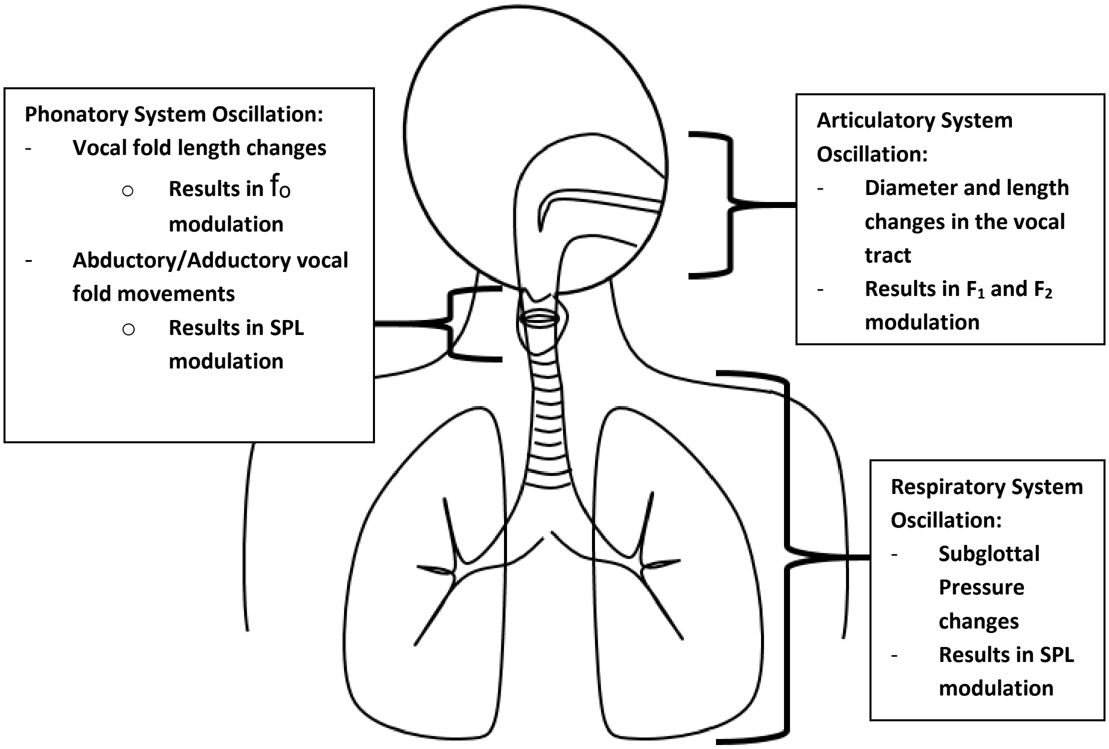



Figure 1. Barkmeier-Kraemer and Story (2010) Conceptual Model of Vocal Tremor

(SPL) during phonation due to subglottal pressure changes associated with rhythmic compression and expansion movements of the thoracic cavity due to tremor affecting muscles of the rib cage, diaphragm, or abdomen (see Figure 1). Oscillation of the articulatory structures is hypothesized to result in acoustic modulation of the formant frequencies (i.e., resonant frequencies). The latter is based upon a model of speech production developed by Brad Story (Story, 1995). This model renders the oral and pharyngeal cavities lined by associated articulators to behave as a resonating chamber that filters the sound produced at the level of the larynx by varying length, diameter, and shape. This resonating chamber is referred to as the *vocal tract*. If an articulator associated with any portion of the vocal tract oscillates (e.g., the base of tongue and posterior oropharyngeal wall region), the result is oscillation of diameter due to alternation of constriction and dilation of the vocal tract, or length changes occurring due to vertical oscillation of the larynx (see Figure 1). Finally, tremor causing oscillation within the phonatory system is hypothesized to result in two different, or combined acoustic modulations: 1) lengthwise oscillation of the vocal folds is hypothesized to predominantly result in modulation of fundamental frequency ($f_o$), and 2) medial/lateral oscillations of the vocal folds (i.e., oscillation causing abduction/adduction of the vocal folds) is hypothesized to predominantly result in modulation of SPL (see Figure 2). Thus, the conceptual model of vocal tremor offers specific predictions regarding acoustic patterns resulting from tremor affecting each of the speech mechanism systems to explain the range of vocal tremor acoustic patterns described in the literature.

The Conceptual Model of Vocal Tremor was developed to help frame future research investigating characteristics of tremor affecting the speech

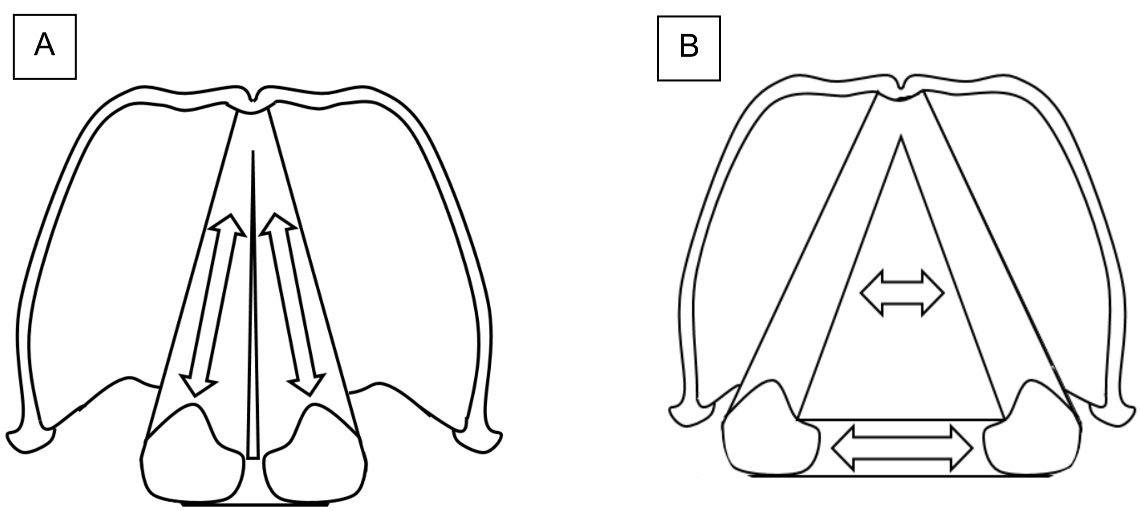



Figure 2. Lengthwise (A) and medial/lateral (B) oscillation directions within the Phonatory System

mechanism and associated acoustic patterns. For a summary of the model, see Table 2. To date, testing of this model has primarily been completed using case-based studies and simulation of tremor within isolated speech mechanism systems.

One example combined case-based testing of vocal tremor and simulation of vocal tremor is a study by Lester and colleagues (Lester, et al., 2013). This study evaluated acoustic patterns in an individual observed to present with lengthwise vocal fold oscillation during sustained phonation as determined using stroboscopic imaging. Although lengthwise vocal fold oscillation was hypothesized within the Conceptual Model of Vocal Tremor to result in a predominance of acoustic modulation of $f_o$, SPL modulation extent was found to predominate. Reevaluation of the original stroboscopic evaluation identified that the laryngeal vestibule appeared to also oscillate in a lengthwise direction associated with vocal fold lengthwise oscillation. Further investigation was completed with consideration that the laryngeal vestibule may serve as part of the vocal tract acting as a resonating chamber and contribute to the acoustic

Table 2. Barkmeier-Kraemer and Story (2010) Summary of Conceptual model of vocal tremor.

| **Speech Mechanism System Affected by Tremor** | **Hypothesized Acoustic Modulation** |
|---|---|
| Respiratory System oscillation of thoracic cavity compression and expansion | Sound Pressure Level (SPL) |
| Phonatory System 1: Vocal fold length oscillation | Fundamental Frequency ($f_o$) |
| Phonatory System 2: Medial/lateral vocal fold oscillation | Sound Pressure Level (SPL) |
| Articulatory System oscillation of diameter and/or length of the vocal tract | Formant Frequencies ($F_1$ and $F_2$) |

patterns predicted for the vocal tract resulting in formant modulation and subsequent SPL modulation.  Acoustic analysis of the vocal tract formants supported that the case under study demonstrated formant modulation consistent with the idea that the laryngeal vestibule contributed to vocal tract oscillation.  To further test the idea of the laryngeal vestibule as a component of the vocal tract for this individual case, an analysis-by-synthesis approach was utilized.  That is, the acoustic characteristics from the case voice recordings were used to model acoustic modulation patterns resulting from oscillation originating within the larynx alone compared to the larynx plus the vocal tract. Systematic analysis of varied possible conditions of laryngeal and vocal tract oscillation patterns and associated acoustic patterns demonstrated that the Conceptual Model of Vocal Tremor helped elucidate the location of tremor within and outside of the vocal folds of one individual and supported that the laryngeal vestibule resonating chamber contributed to acoustic modulation patterns as predicted for the vocal tract (Lester et al., 2013).

Although the case example described above was helpful for testing the Conceptual Model of Vocal Tremor, general testing on groups of individuals with vocal tremor has not yet been completed.  One reason for this arises due to difficulty successfully identifying individuals representing tremor isolated within each system of the speech mechanism.  Thus, the question arises whether a human demonstration of volitional oscillation within one subsystem of the speech mechanism could be used as a surrogate approach to test the Conceptual Model of Vocal Tremor (Barkmeier-Kraemer & Story, 2010).

One possible approach to studying vocal tremor acoustic patterns associated with oscillation of speech mechanism structures is to study volitional modulation of the voice, or vibrato. Western classical singing proponents consider vibrato to be the “quasi automatic” result of correct singing technique, used by singers to produce an aesthetically pleasing singing voice (Sundberg, 1994). Vibrato shares many similar acoustic features to vocal tremor such as rate and extent of $f_o$ and SPL (Anand, Shrivastav, Wingate, & Chheda, 2012; Anand, Wingate, Smith, & Shrivastav, 2012). Similar to vocal tremor, typical vibrato rate is between 4-7 Hz (Anand, Widgate, et al., 2012; Guzman et al., 2012; Howes, Callaghan, Davis, Kenny, & Thorpe, 2004; Prame, 1994; Ramig & Shipp, 1987; Seashore, 1931; Sundberg, 1994; Titze, Story, Smith, & Long, 2002; Watson, Williams, & James, 2012) with an extent of $f_o$ modulation between 0.25-2 semitones (Anand, Windgate, et al., 2012; Guzman, et al., 2012; Howes, et al., 2003; Prame 1994; Seashore 1931). One semitone is equivalent to a modulating extent of about 6%. Therefore, 0.25-2 semitones would equate to an extent of about 2-12%. As reported earlier, a typical vocal tremor rate is between 4-8 Hz and is associated with a 3-17% extent of $f_o$.

Also similar to vocal tremor, vibrato is produced by oscillation of structures within the speech mechanism resulting in acoustic modulation. Based on prior literature, vibrato studied in trained singers’ results from oscillation in laryngeal and respiratory structures. Vibrato is predominantly the result of alternating contraction between the cricothyroid (CT) and a combination of the thyroarytenoid (TA) and lateral cricoarytenoid (LCA) resulting in laryngeal oscillations (Dromey & Smith, 2008; Hsiao, Solomon, Luschei, & Titze, 1994; Sundberg 1994; Titze, et al., 2002). Given the roles of medial/lateral or lengthwise change in the positioning of the vocal folds associated with LCA and TA/CT contractions, respectively, laryngeal oscillations associated with vibrato would be expected to result in modulation of SPL and $f_o$ acoustic components, respectively.

Although the predominant involvement of laryngeal musculature appears associated with TA/LCA and CT musculature, supplementary respiratory (i.e., sternocleidomastoid) and postural (e.g., scalenes and latissimus dorsi) musculature also co-varied activation with production of $f_o$ modulation during production of vibrato (Pettersen & Westgaard, 2005; Watson, et al., 2012). However, the role of supplementary respiratory musculature was difficult to interpret from the description in these studies. It is possible that supplementary respiratory musculature contributes to the artistic aim to achieve balanced participation between the respiratory and laryngeal systems. For example, as laryngeal movements associated with production of vibrato occur, SPL changes can occur due to oscillation in laryngeal valving patterns possibly requiring supplementary respiratory musculature to respond in an opposite and similar pattern to achieve stability across speech structures during vibrato performance. Given that the involvement of the primary expiratory and inspiratory respiratory musculature was not found, it is likely that the role of supplementary respiratory musculature was not related to respiratory pressure generation. Therefore, supplementary respiratory musculature likely serves an antagonistic function during vibrato generation to maintain stable laryngeal positioning and performance of the speech mechanism during production of vibrato during singing.

Instruction on the production of vibrato involves extensive training of techniques that aim to manipulate and balance the use of the respiratory and laryngeal structures to facilitate modulation of the voice (Kirkpatrick, 2008). Specifically, vibrato associated with Western classical singing is trained in singers by teaching the techniques to facilitate oscillation of laryngeal structures via a reflexive struggle between the CT and TA musculature (Titze et al., 2002). According to the conceptual model, this would result in lengthwise vocal fold oscillation resulting in predominant extent of modulation of $f_o$ in the acoustic signal.

Although supplementary respiratory musculature has been implicated during production of vibrato, respiratory involvement during vibrato is considered a sign of poor vibrato technique (Kirkpatrick, 2008). However, a healthy use of the respiratory system for modulation of the voice can be used to facilitate improved respiratory-phonatory coordination during phonation. One method documented as successful in achieving this goal is the Accent Method Voice Therapy (AMVT) (Kotby & Fex, 1998). AMVT involves teaching individuals to use rhythmic accentuated phoneme productions (Kotby & Fex, 1998) to enhance phonatory-respiratory coordination during voice production. The rhythmic accentuation during phonation results from a focus on expiratory rhythmic pulsing through volitional abdomino-diaphragmatic contractions. Accordingly, these volitional abdominal accents could be studied to determine whether individuals can volitionally isolate respiratory oscillation to produce voice modulation predominantly associated with SPL modulation as predicted by the Conceptual Model of Vocal Tremor. One study reported a correlation between volitional abdominal accents characteristic of AMVT and a generally associated increase in SPL and $f_o$ (Kotby, Shiromoto, & Hirano, 1993). Although covariation between SPL and $f_o$ was not determined in this study, it did confirm SPL linkage to volitional abdominal accents. Thus, the AMVT approach to volitional respiratory system accent production using a rhythmic pattern could be used to test the Conceptual Model of Vocal Tremor hypothesis of respiratory system contribution to voice modulation.

## Statement of Purpose

Vocal tremor typically presents simultaneously across speech structures making it difficult to examine predicted contributions of individual portions of the speech mechanism to predicted acoustic patterns. However, vibrato and AMVT offer two volitional methods for testing hypothesized contributions of the laryngeal and respiratory oscillations to acoustic modulation patterns. In addition, testing these two volitional manipulations of voice production could elucidate whether the laryngeal and respiratory systems can be isolated from each other during a voicing task, or are linked in movement patterns. That is, these voluntary forms of voice modulation (i.e., vibrato and AMVT) could occur by isolated oscillation of targeted speech structures or may require coordinated cooscillation of speech structures. If oscillation across systems is demonstrated, this would support the possibility of volitional motor planning linkages between speech mechanism structures that might apply to individuals with vocal tremor in which multiple speech structures appear to be simultaneously affected.

The purpose of this study is to investigate laryngeal and respiratory system physiologic and acoustic correlates as predicted by the Conceptual Model of Vocal Tremor using trained singers to volitionally produce vibrato and rhythmic accented production of loudness (i.e., AMVT). The hypothesized contribution of the respiratory and laryngeal systems to acoustic modulation patterns are (see Table 3):

1) Rhythmic accented production of loudness using AMVT via chest wall expiratory movements is hypothesized to be associated with greater extent of SPL compared to $f_o$ modulation.
2) Production of vibrato via lengthwise vocal fold oscillation within the larynx is hypothesized to be associated with greater extent of $f_o$ compared to SPL modulation.

Table 3. Aims of this study

| **Aims** | **Independent Variable** | **Dependent Variables** | **Hypothesized Outcome** |
|---|---|---|---|
| 1. Study acoustic modulation patterns associated with respiratory system oscillation | Rhythmic accented loudness modulation achieved by AMVT production during sustained phonation | a. Chest wall oscillation rate and extent<br>b. SPL modulation rate and extent<br>c. $f_o$ modulation rate and extent | Chest wall movements during accented loudness production will be associated with the rate and extent of SPL > $f_o$ modulation |
| 2. Study acoustic modulation patterns associated with laryngeal structure oscillation | Rhythmic $f_o$ modulation achieved by vibrato production during sustained phonation | a. Vocal Fold oscillation rate and extent<br>b. $f_o$ modulation rate and extent<br>c. SPL modulation rate and extent | Laryngeal oscillation movements during vibrato will be associated with rate and extent of $f_o$ > SPL modulation |

# METHODS

## Subjects

This study was approved by the University of Utah Institutional Review Board (IRB, protocol #IRB 00084972). A total of 11 singers without report of voicing problems or singing complaints responded to IRB-approved flyers distributed through social media, campus postings, and email listserves. Subjects were required to be 40-65 years of age with no less than 5 years as a trained singer and without report of voicing or singing problems prior to consent and completion of screening procedures. All consented participants were screened for the presence of singing and voicing problems (see the description of the screening procedures below). One individual did not meet inclusion criteria out of the 11 volunteers for this study. Recruitment continued until a total of 10 singers meeting inclusion criteria were recruited.

## Screening Procedures

All consented participants completed the Voice Handicap Index (VHI) (Jacobson, et al., 1997) and the Singing Voice Handicap Index (Singing VHI) (Cohen, et al., 2007) to determine whether voice complaints or singing problems, respectively, were indicated by abnormal scores (>20 points total score). In addition, participants completed a questionnaire regarding their singing training and genre to assure that participants completed a minimum of 5 years of training of the singing voice in Western Classical Singing with a self-identified skill in producing vibrato and the capability of producing rhythmic accented production of loudness during sustained phonation (see Appendix a). Of the 10 final participants, 2 participants initially demonstrated total scores in the abnormal range on the VHI; however, both individuals clarified that they misunderstood the VHI rating descriptors and adjusted their scores into the normal range during discussion regarding the outcomes of the screening procedures.

## Procedures

Respiratory kinematic, audio, and laryngeal imaging signals were recorded simultaneously during sustained phonation tasks. The respiratory kinematic, audio, and laryngeal imaging signals were synchronized for analysis of corresponding laryngeal and respiratory kinematic and acoustic patterns. An example of the simultaneous recording for comparison of laryngeal endoscopy with simultaneous audio and respiratory kinematic signals can be viewed in Figure 3.

## Respiratory Kinematic Recordings

### Respiratory Kinematic Equipment

Two piezo respiratory belt transducers from AD Instruments (Model MLT 1132) were used to measure chest wall movement of the participants. The transducers were connected to the AD Instruments 8-channel PowerLab (Model PL 3516) console and LabChart Pro (version 8.1), an AD Instruments software program. Two piezoelectric respiratory belt transducers were used to measure respiratory chest wall oscillatory patterns. Each respiband was worn around the

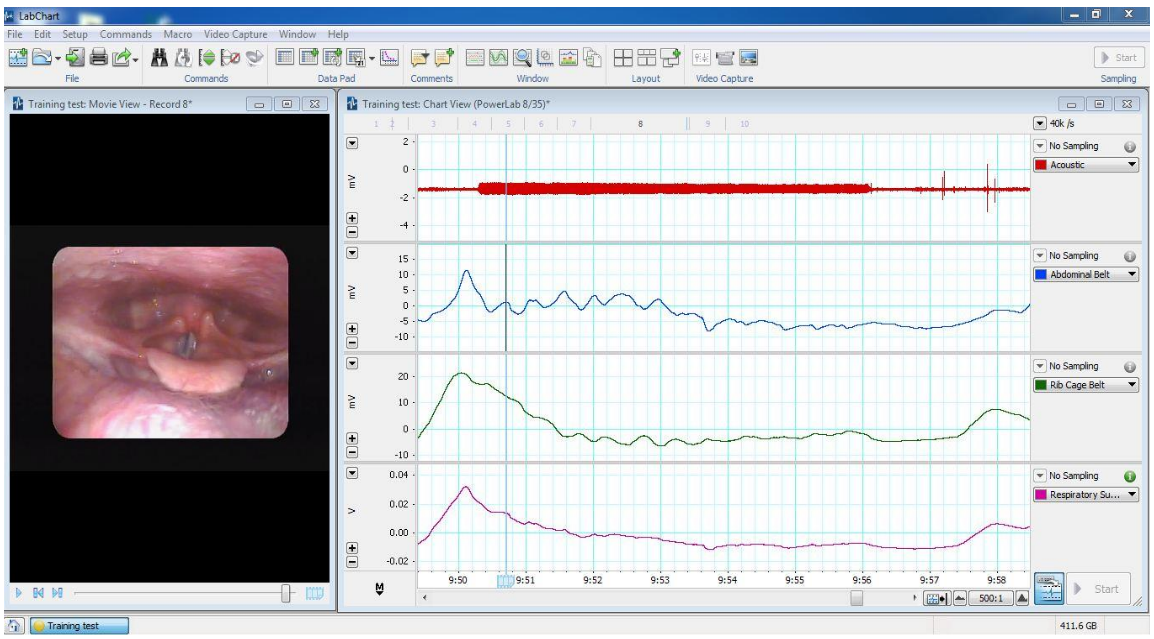



Figure 3. LabChart Pro display of simultaneously recorded laryngeal images and acoustic and respiratory signals.

participant's chest wall with one band placed over the rib cage and the other placed over the abdominal region. The respiratory belt transducer responsible for measuring rib cage movement was secured around the circumference of the rib cage at the approximate level of the nipple, running across the sternum in the front and the upper back. The respiratory belt transducer responsible for measuring abdominal movement was secured around the circumference of the abdomen inferior to the ribcage in the front and the lower back. During the setup, the respiratory belt transducers were positioned to avoid slipping or repositioning, and to reflect rib cage and abdominal movements during inhalation, exhalation, and phonation. Also, the recorded signal was checked to ensure the entire range of chest wall expansion and compression could be captured within the range of
the LabChart channel.

## Respiratory Kinematic Signal Calibration

To calibrate for differences in size and range of utilization of the vital capacity during singing tasks across participants, the respiratory signal was normalized across the maximum range of chest wall expansion to compression during a vital capacity maneuver task. Participants were instructed to inhale air until they could inhale no further and then to exhale until they could exhale no further while standing upright. This task was repeated three times. The maximum recorded value associated with the maximum inhalation maneuver was set to represent 100% vital capacity, whereas the minimum value associated with the maximum exhalation maneuver was set to represent 0% vital capacity. The calibration was performed within LabChart and applied to the entire recording for each participant to enable comparison of respiratory modulation measures within and between participants.

### Respiratory Kinematic Procedures

The signals from the respiratory transducers were recorded in LabChart (AD Instruments, Version 8.1). Signals were recorded showing the degree of expansion and compression of the rib cage and abdomen during quiet breathing and during singing tasks. A summated signal from each portion of the chest wall was recorded directly onto the AD Instruments LabChart at a sampling rate of 10 kHz. The oscillatory movements of the chest wall were measured for rate and extent relative to acoustic vibrato and accent (AMVT) patterns.

## Acoustic Recordings

### Acoustic Recording Equipment

Acoustic recordings were obtained using an AKG head-mounted condenser microphone (model C520) and preamplifier (Symetrix 302 Dual Mic Pre-Amp) such that signals were recorded using the AD Instruments 8-channel PowerLab (Model PL 3516) and LabChart Pro (version 8.1) into the software simultaneously with laryngeal imaging and respiratory kinematic signals. Audio signals were recorded at a sampling rate of 40 kHz.

### Acoustic Recording Procedures

Once the participant verbally expressed readiness to begin recordings, the experimental sessions began by providing instruction to the participant to sustain three different vowels, /a/, /u/ and /i/, for the duration of 5 s each. These vowels were selected to represent “corner vowels” on the English Vowel Chart, produced using a high forward (i.e., /i/) versus high back (i.e., /u/) and low back (i.e., /a/) tongue position. It was anticipated that views of the larynx would not be obstructed by the tongue during production of the two high corner vowels compared to the occluded views of the larynx during production of the low back vowel, /a/. The differing vocal production techniques utilized across participants produced a variety of imaging results, with visibility of the larynx ranging from fully visible to fully obstructed.

Although 3 corner vowels were recorded, only the recordings of /i/ were analyzed to test the aims of this thesis. The additional vowel recordings were conducted as part of a larger data collection for future analysis outside of the aims of this thesis.

Each participant produced three trials of each vowel with vibrato and rhythmic accented loudness production using AMVT at comfortable pitch and loudness. The order of vowel production was not counterbalanced across participants to assure similar conditions of production for all participants. However, the order of voice modulation condition for each vowel (vibrato versus AMVT) was counterbalanced. Three trials for each vowel and voice modulation condition were produced by each participant. The sequence for production of each voice modulation condition for each participant was determined in advance of the recording sessions to assure that equal representation of voice modulation condition sequencing occurs across all participants. Thus, each participant produced 18 stimuli (3 vowels: /a/, /u/, and /i/) x 2 voice modulation types (vibrato and AMVT) x 3 trials = 18).

## Laryngeal Imaging

### Laryngeal Imaging Equipment

Laryngeal imaging was obtained using the Pentax Medical Nasolaryngoscope System (KayPentax, model 9310HD) and nasoendoscope (KayPentax, VNL-1070STK) simultaneously with audio and respiratory kinematic signals via AD Instruments 8-channel PowerLab (Model PL 3516) and LabChart Pro (version 8.1) hardware/software enabling simultaneous video capture (Figure 3).

### Laryngeal Imaging Procedures

Laryngeal imaging was initiated once the audio microphone and respiratory kinematic bands were placed on the participant. Laryngeal imaging was obtained using flexible nasoendoscopy to minimize impact on vocal tract configuration during recording of voicing tasks. The laryngeal imaging procedures were completed by the supervising thesis advisor (i.e., Dr. Barkmeier-Kraemer). Topical anesthesia (4% viscous lidocaine) was applied using a Qtip placed within the left or right entry to the nasal passage and anterior middle meatus based upon the preference of the subject. The topical anesthesia was also applied to the scope tip portion of the nasoendoscope posterior to the lens to minimize discomfort during endoscope placement for laryngeal imaging. All participants tolerated the scope placement and experimental procedures without additional need for topical anesthesia.

The nasoendoscope was passed transnasally until the larynx and vocal folds were visible in entirety. Once the nasoendoscope was positioned for optimal viewing of the larynx during voicing, the participant was instructed to "warm up" until they felt accustomed to the scope placement during singing. Once the participant conveyed readiness, the experimental speech tasks were initiated as described within the audio recording procedures.

# DATA COLLECTION AND MEASURES

## Classification of Participant Voice Modulation Conditions by Expert Judges

Three expert judges of the singing voice with at least five years of experience instructing singers were recruited from the faculty of the University of Utah School of Music and the School of Musical Theater to complete audio-perceptual judgments of participant voice recordings and classify each participant's recordings as one of the voice modulation types under study.

## Hearing Screenings

Each expert judge underwent a hearing screening administered by a certified SLP to assure typical hearing. The screening tested hearing ability at 500, 1000, 2000, and 4000 Hz at 25 dB SPL in each ear using a pure-tone audiometer and earphones while sitting in a sound treated booth. The 3 expert judges included in this study passed the hearing screening according to the above criteria.

## Listening Task

Each expert judge individually listened to each participant's audio recordings of vibrato and AMVT for each audio recorded trial of /i/. The 3 audio recording trials of the /i/ vowel in each voice modulation condition were concatenated into one file for presentation to judges for each of the voice modulation conditions (AMVT vs. vibrato). Each file was presented 3 times for intrarater reliability purposes. Therefore, 60 total audio samples were presented to the expert judges (1 vowel x 2 modulation types x 3 presentations of each file sample x 10 participants = 60 total samples).

These audio files were presented for classification by judges using a randomized presentation order. Listener stimuli were presented using individual PowerPoint slides displaying each audio file for evaluation. Judges could proceed at their own rate through the audio files and replay each file as many times as necessary to rate the classification of voicing method. Judges listened to audio file presentations via a high fidelity headset (Sennheiser HD 429) at a comfortable loudness level while sitting in a sound treated booth. Each listening trial was classified by each judge as “vibrato,” “accented loudness,” or “unable to classify.” Judges recorded their ratings for each listening trial onto a formatted scoring sheet such that the classification of a condition was indicated by circling the choice that best characterizes what the judge perceived.

Classification of each stimulus was determined by comparing judge classification ratings to the intended production. A match between judge ratings and the intended production was scored as an accurate production. A mismatch between judge ratings and the intended production was scored as an inaccurate production. Rating scores for the total proportion of participant conditions scored as accurate were averaged across the three judges’ scores. Recordings from participants judged as accurate $\geq$ 75% of the time were used for experimental analysis. Recordings that did not meet the accuracy criteria above were noted and reviewed by the authors. A mismatch occurred for the vibrato condition of 2 participants and for the accent condition for 1 participant (see Table 4). The acoustic and respiratory signals from these files were visually inspected and compared to other recordings judged accurately by judges and did not appear acoustically dissimilar (see Figure 4A and 4B). Thus, the measures from the three files judged inconsistently were included within the final data set analyzed for this study.

Physiologic Measurement of all Recordings

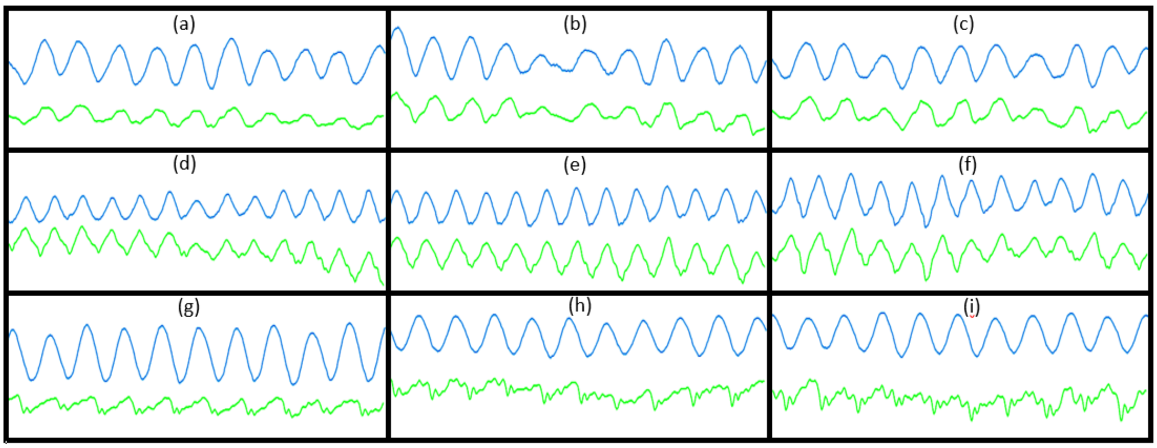
All simultaneously recorded respiratory kinematic, acoustic, and laryngeal endoscopic signals were saved and stored for each subject recording session. Two seconds from the midportion of each recorded experimental trial was selected for analysis. A random number generator was used to code each file into randomized order to assure blinding of condition, trial, and subject during measurement of physiologic signals. Nine additional files were randomly selected (15%) of the total number of files to be analyzed (*n = 60*) so that intrarater reliability could be assessed for each physiologic signal measurement method. Once all measures were completed across all physiologic signals, files were decoded for statistical analysis.

Table 4. Percent agreement between expert judges and intended production condition.

| Condition | S01 | S03 | S04 | S05 | S06 | S07 | S08 | S09 | S10 | S11 |
|---|---|---|---|---|---|---|---|---|---|---|
| Vibrato | 89% | ***44%** | ***44%** | 100% | 100% | 100% | 100% | 89% | 89% | 89% |
| AMVT | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 89% | ***67%** | 100% |

*This production condition did not meet accuracy criteria and was subject to review by the authors.

A.




B.

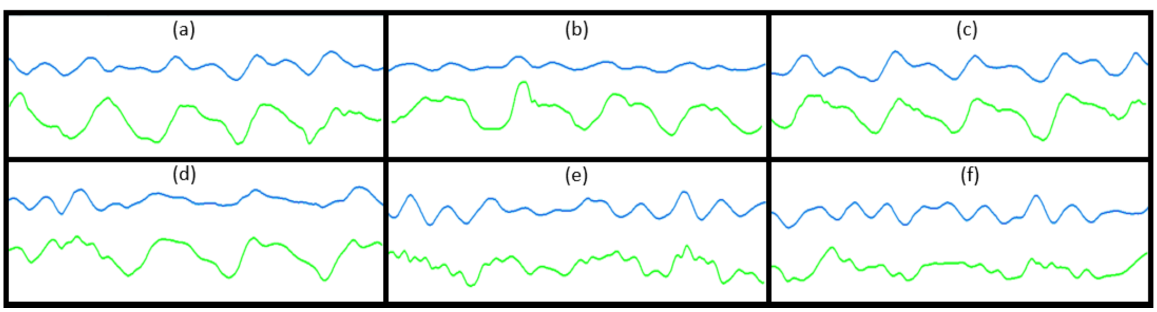



Figure 4. A comparison of signals rated for each voicing condition (i.e., vibrato and AMVT). A. A comparison of signals rated for the vibrato condition from the two subjects rated with 44% expert agreement from S03 (a-c) and S04 (d-f) and signals with 100% expert agreement from S05 (g-i) versus. B. A comparison of signals rated for the AMVT condition with 67% expert agreement from S10 (a-c) and 100% expert agreement from S05 (d-f).

## Respiratory Kinematic Analysis

Respiratory oscillation movements were analyzed during the same time frame analyzed for the audio recordings to compare simultaneous respiratory kinematic and acoustic patterns.

### Respiratory Kinematic Oscillation Rate

The rate of respiratory kinematic oscillation was determined by identifying peak-to-peak or trough-to-trough patterns of the modulating waveform per second from the summated rib cage and abdominal voltage signal (see Figure 5). The rate of oscillation was determined from the number of cycles recorded per second (Hz).

### Respiratory Kinematic Measure Adjustments for Slope

Given that participants sustained phonation while producing vibrato or AMVT, the lung volume continually decreased across the recorded trials.  Thus, adjustments to the respiratory measures were needed to reduce, or eliminate the changing lung volume effect on measures obtained over the duration of the recording.  To achieve this, the mean slope of each signal was calculated for each 2-s segment and factored in to each maximum and minimum value obtained to adjust for the slope (see Figure 6). The mean slope of the entire signal was multiplied by the time point associated with the maximum or minimum value within the 2-s signal and then added to the value measured at the peak and valley values of the modulating respiratory kinematic signal. Note that the time point value is based on a 0-2 s time interval, rather than the timestamp of the entire recording. For example, the 2-s window in Figure 6 took place at

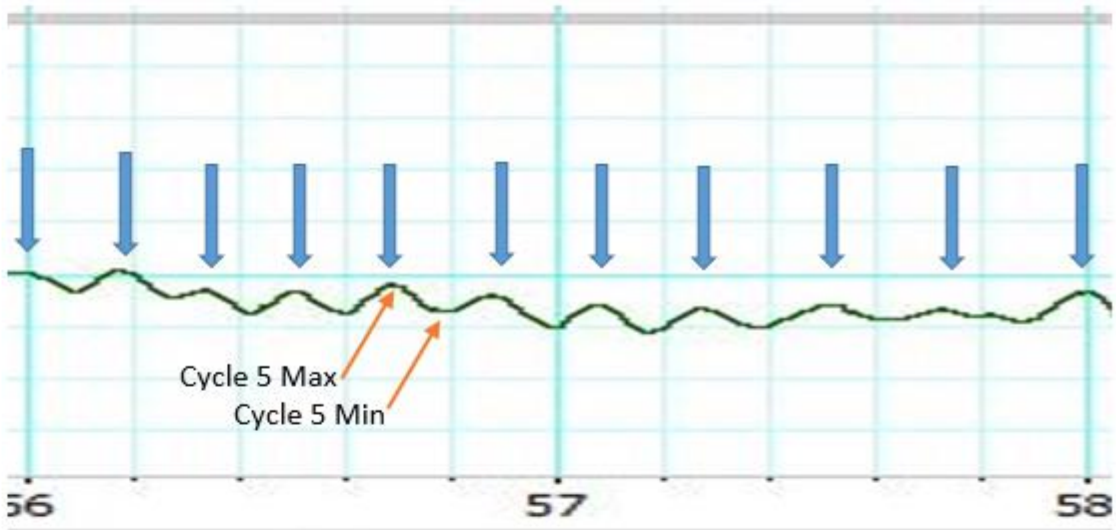



Figure 5. Example of determining rate for respiratory kinematic oscillation. Each arrow marks the peak of each modulation cycle displayed in the 2-s window. A total of 11 peak-to-peak cycles are shown in the 2-s window giving a 5.5 Hz respiratory kinematic rate.

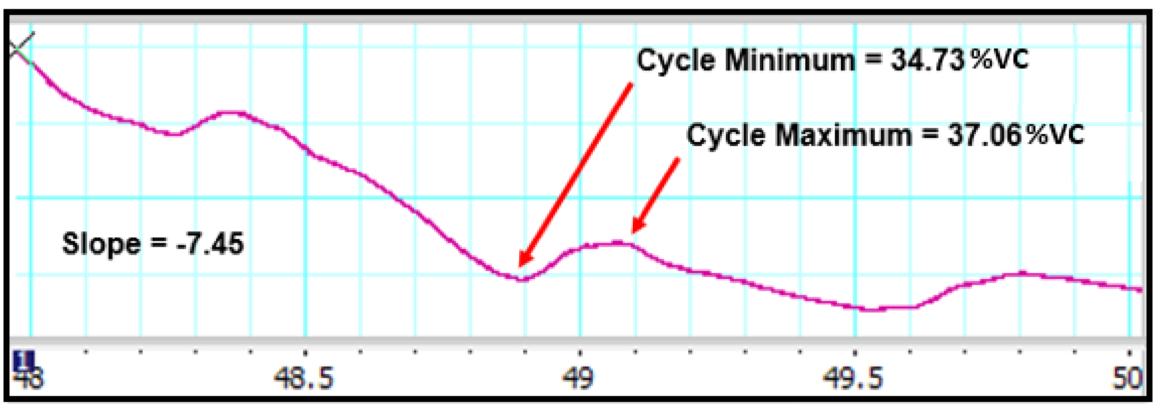



Figure 6. Example of measuring extent of respiratory kinematic oscillation. The minimum and maximum values associated with summated rib cage and abdominal movements in the figure represent the original data points. The original data points were corrected before extent was calculated. After adjustment for the sloping values, the relative %VC extent was calculated as described above.

timestamp 48-50 s. Therefore, a timestamp of 48.783 s for the data point would be equal to an adjusted time point value of 0.783 s. The equation used to adjust the kinematic %vital capacity (%VC) measures to eliminate the slope effects is shown in equation 1 below:

$$\mathbf{y_{corrected} = y_{original} + [mean_{slope} * time\ point_{max/min}]} \qquad \mathbf{(1)}$$

Thus, with reference to the values displayed in Figure 6, the following calculations were completed to obtain the adjusted maximum and minimum values of one respiratory kinematic cycle:

$$\mathbf{Cycle\ 2\ minimum_{corrected} = 34.73\%VC + [-7.45 * 0.783\ s] = 28.90\%VC}$$

$$\mathbf{Cycle\ 2\ maximum_{corrected} = 37.06\%VC + [-7.45 * 0.691\ s] = 30.30\%VC}$$

## Respiratory Kinematic Oscillation Extent

The extent of respiratory kinematic modulation was determined by measuring the maximum and minimum %VC from the summated rib cage and abdominal wall voltage signal for each oscillation cycle after the slope adjustment was applied. The maximum and minimum %VC values were identified by selecting the peak and trough within the summated rib cage and abdominal wall signal in LabChart. Then, using the LabChart data pad functions for calculating maximum and minimum values within a selection, the values were automatically populated in the data pad spreadsheet. The values were then entered into an Microsoft Excel spreadsheet for further calculations.

After the original data points were adjusted for the sloping signal, the %VC extent was calculated by dividing the difference between the minimum

%VC value and the maximum %VC value for one cycle by the sum of the maximum and minimum %VC values for that same cycle and multiplying by 100 to obtain a percentage value. All oscillation cycle relative %VC extent values were averaged for each trial. Figure 6 can be used again for an example of respiratory kinematic measurement. Using the adjusted values previously calculated, the following method was used to determine the relative extent of respiratory kinematic modulation in equation 2:

$$\textbf{Extent} = (\textbf{Cycle}_{\textbf{Max}} - \textbf{Cycle}_{\textbf{Min}}) / (\textbf{Cycle}_{\textbf{Max}} + \textbf{Cycle}_{\textbf{Min}}) * 100 \qquad (2)$$

$$\textbf{Extent of Cycle 2} = (34.15 - 27.85) / (34.15 + 27.85) * 100 = 10.2\%$$

<u>Acoustic Measures</u>

Acoustic modulation patterns of $f_o$ and SPL were measured from the middle 2-s portion of each recorded trial. The $f_o$ and SPL values within each selected acoustic segment for analysis were displayed in Praat (Boersma & Weenink, 2015; v 5.4.09) for analysis of rate and extent of modulation.

Acoustic Modulation Rate

The 2-s segments of $f_o$ and SPL modulation were analyzed for rate by counting the number of peak-to-peak or trough-to-trough $f_o$ and SPL modulation cycles displayed and dividing by 2-s to record rate of modulation in Hertz (cycles/s) (see Figure 7). The number of $f_o$ and SPL modulation cycles per s was determined for the signals displayed in Figure 7 with the following equation 3:

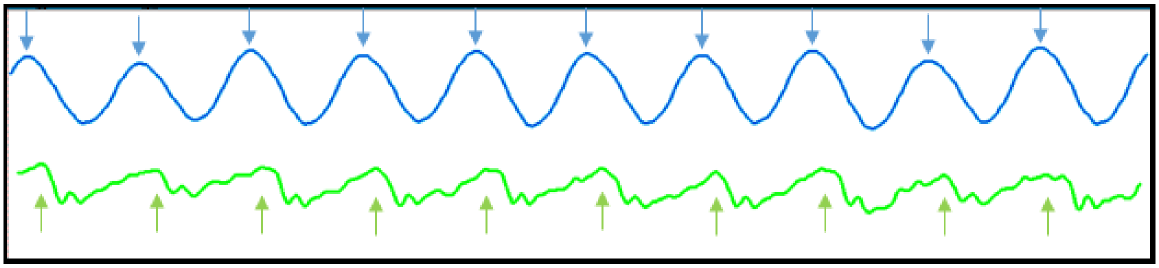


Figure 7. Example of $f_o$ (top line) and SPL (bottom line) plot of vibrato within Praat. Arrows have been added to the signal to indicate the beginning of the cycle.

**Rate (Hz) = (Number of cycles) / (time (s))** **(3)**

**Rate for $f_o$ (top signal) is 9.5 cycles / 2-s = 4.8 Hz**

**Rate for SPL (bottom signal) is 9.5 cycles / 2-s = 4.8 Hz**

## Acoustic Modulation Extent

The extent of $f_o$ and SPL modulation for each cycle was determined by measuring the maximum and the minimum values from the peak and valley portions of each cycle (see Figure 8). The maximum and minimum values were identified by importing the 2-s portion of the acoustic files being analyzed into Praat. The modulation cycles were identified using the peak to peak or trough to trough analysis (see Figure 8). Each cycle was then highlighted by dragging the cursor across one cycle. Then, functions were completed within Praat to calculate the maximum and minimum values of $f_o$ and SPL (i.e., get minimum pitch, get maximum pitch, get minimum intensity, and get maximum intensity). The respective values were then entered into an MS Excel spreadsheet for calculation of the extent values.

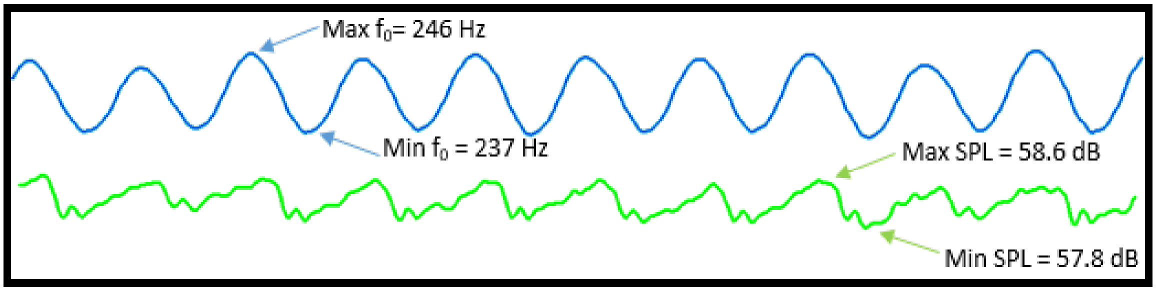



Figure 8. Example of $f_o$ (top line) and SPL (bottom line) plot of vibrato within Praat. Arrows have been added to the signal to indicate the maximum and minimum points of cycle 3 ($f_o$) and cycle 8 (SPL).

$f_o$ Extent Measures

Calculation of $f_o$ extent was completed by subtracting the minimum $f_o$ value from the maximum $f_o$ value and dividing the resulting value by the sum of the maximum and minimum $f_o$ values of that cycle and multiplying by 100 to determine a percentage value. This was repeated for all $f_o$ modulation cycles within the selected segment of each trial as shown in the equation 4 below for Figure 8:

$$\textbf{Extent} = (f_o \textbf{ Max} - f_o \textbf{ Min}) / (f_o \textbf{ Max} + f_o \textbf{ Min}) * 100 \qquad \textbf{(4)}$$

$$\textbf{Figure 8 Extent } f_o = (246 \text{ Hz} - 237 \text{ Hz}) / (246 \text{ Hz} + 237 \text{ Hz}) * 100 = 1.9\%$$

SPL Extent Measures

The extent of SPL modulation was determined from the maximum and minimum dB SPL values associated with SPL modulation (see Figure 8). SPL values were converted to a linear scale, Pascals, so that the same calculation method used for $f_o$ extent could be performed for SPL extent. Using the values shown in Figure 8 below, the following equation 5 offers an example of one cycle of SPL modulation extent calculation:

$$\textbf{SPL Extent} = (\textbf{SPL Max} – \textbf{SPL Min}) / (\textbf{SPL Max} + \textbf{SPL Min}) * 100 \qquad (5)$$

$$\textbf{Figure 8 Extent SPL} = (.017\ \textbf{Pa} - .016\ \textbf{Pa}) / (.017\ \textbf{Pa} + .016\ \textbf{Pa}) * 100 = 3.03\%$$

## Laryngeal Imaging Kinematic Analysis

Frame by frame analysis of laryngeal oscillatory movements was completed to determine the predominant pattern of laryngeal movement associated with each voice modulation condition (vibrato vs. AMVT). Laryngeal oscillation movements were analyzed from a similar or the same 2-s duration segment as the respiratory kinematic and acoustic signals for each experimental trial. Adjustments in the portion of the endoscopic recording were made if pharyngeal or laryngeal postures occluded views of the vocal folds. During the latter situations, the 2-s segment analyzed was shifted earlier or later as needed to assure continuous views of the vocal folds for kinematic analysis. Given the subjective impression that laryngeal movements remained continuous during all trials, it was not expected that analysis from a shifted time segment would impact measurement outcomes. The maximum and minimum range of vocal fold movement in the anterior/posterior (i.e., lengthwise) and medial/lateral (i.e., abductor/adductor) directions was measured to determine laryngeal oscillation rate and extent for comparison to acoustic and respiratory kinematic modulation patterns. The endoscopic video recordings for each subject were imported into QuickTime to select each of the mid-portion 2-s segments analyzed for the acoustic and respiratory kinematic signals. The maximum and minimum movement frames associated with each laryngeal movement cycle within the analyzed segment were copied and imported into ImageJ (October, 2015) for measurement.

## Laryngeal Oscillation Rate

Laryngeal oscillation rate was determined by recording the number of laryngeal oscillatory cycles obtained during the 2-s segment analyzed for each trial divided by 2 s to determine the rate in Hertz (cycles/s).

## Laryngeal Oscillation Extent

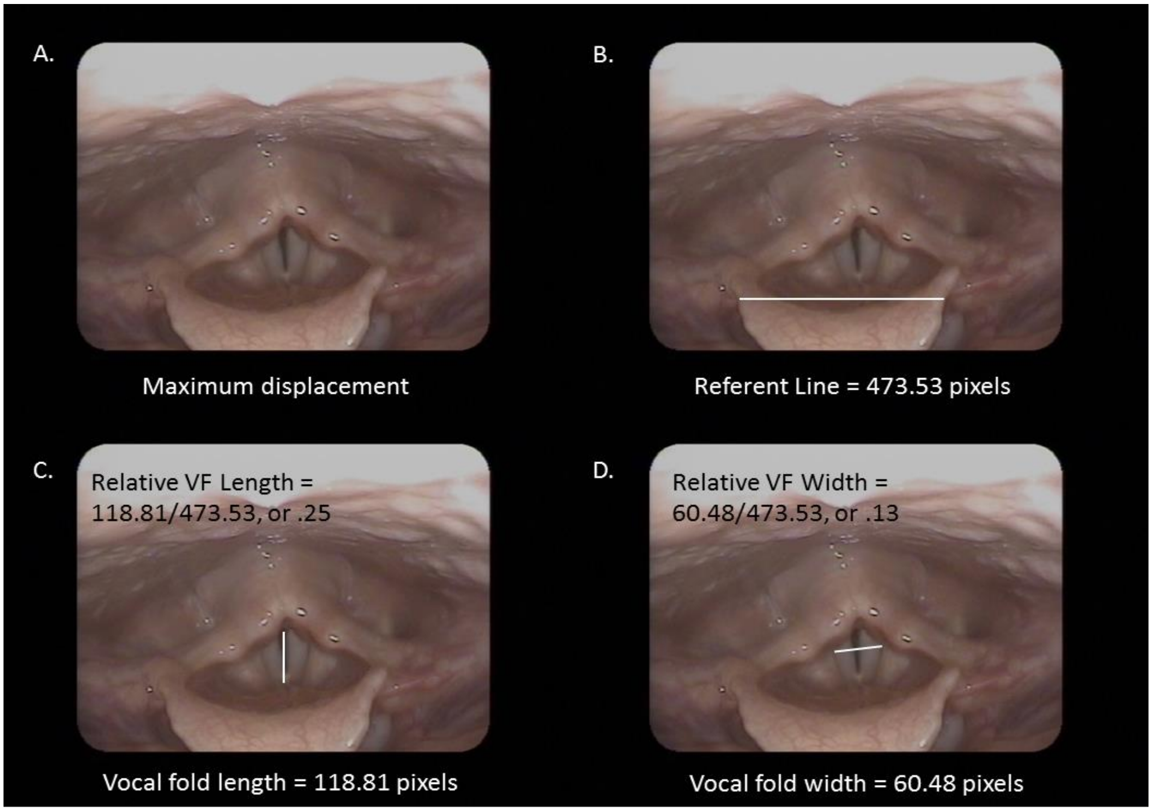
Extent of laryngeal oscillation was measured by identifying image frames displaying the minimum and maximum displacement of laryngeal structures/vocal folds during the predominant direction of oscillation (i.e., lengthwise versus abduction/adduction). The lens to larynx distance varied during recordings, requiring image measures to be normalized by creating a ratio of distance (unit = pixels) between laryngeal movement measures and an anatomical measure observed to remain constant (e.g., width of the epiglottis apex).

### Referent Anatomical Distance Measures

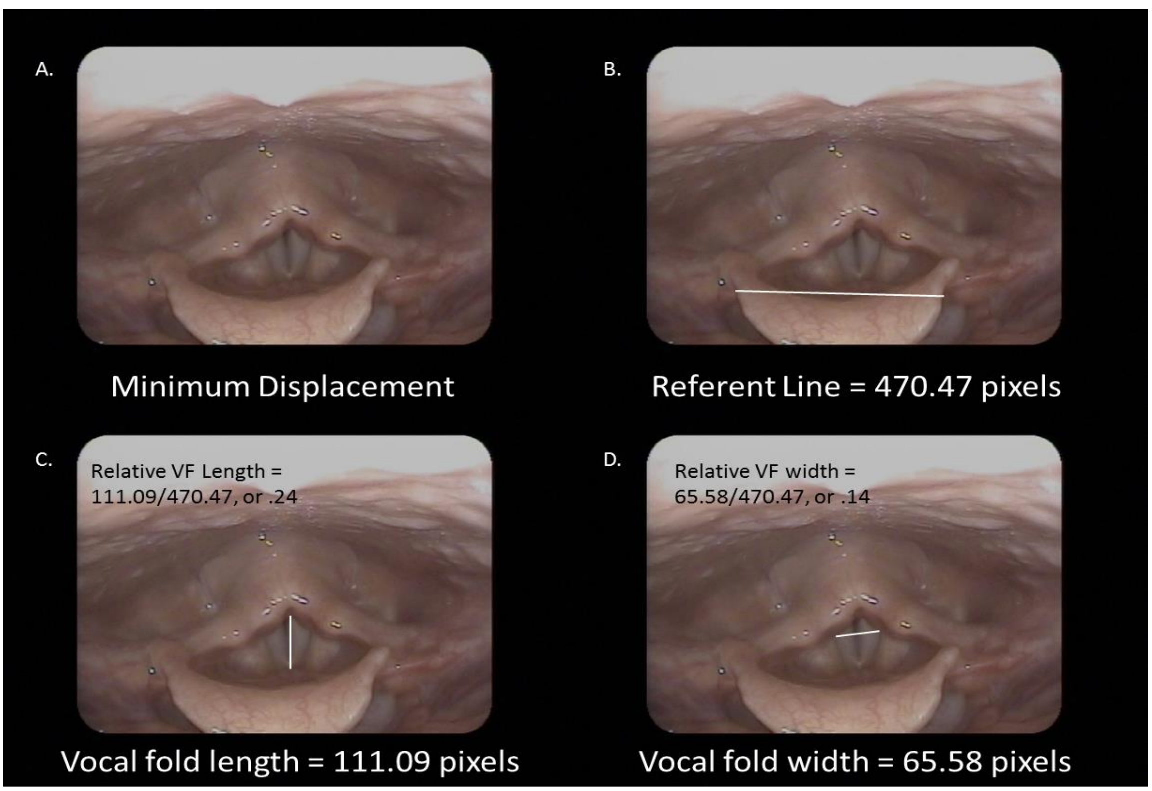
Individual frames judged to exhibit the maximum displacement end points of laryngeal oscillation were selected and saved for analysis within ImageJ software (Rasband, 2015). The referent anatomical distance between two constant and clearly identifiable locations measuring the interarytenoid distance was measured for each maximum and minimum cyclic displacement image (see Figure 9, Part A and B). This was accomplished by drawing a line between the two referent image points using the ImageJ line tool and recording the length of the line in pixels.

Figure 9. An example of laryngeal imaging measures for the first end point of one laryngeal oscillatory cycle. Each panel displays A) the image analyzed, B) the anatomical referent line measure, C) the relative measure of vocal fold length, and D) the relative measure of interarytenoid distance associated with the first end point of one laryngeal oscillation cycle. B. Example of laryngeal imaging measures for the second end point of one laryngeal oscillatory cycle. Each panel displays A) the image analyzed, B) the anatomical referent line measure, C) the relative measure of vocal fold length, and D) the relative measure of interarytenoid distance associated with the second end point of one laryngeal oscillation cycle.

A.


A.
B.
Maximum displacement
Referent Line = 473.53 pixels
C.
Relative VF Length = 118.81/473.53, or .25
D.
Relative VF Width = 60.48/473.53, or .13
Vocal fold length = 118.81 pixels
Vocal fold width = 60.48 pixels

B.


A.
B.
Minimum Displacement
Referent Line = 470.47 pixels
C.
Relative VF Length = 111.09/470.47, or .24
D.
Relative VF width = 65.58/470.47, or .14
Vocal fold length = 111.09 pixels
Vocal fold width = 65.58 pixels

Laryngeal Lengthwise Extent Measures

The length of the vocal folds during maximum and minimum laryngeal cyclic movements was measured by drawing a line from the anterior commissure (or most anterior visible portion of the vocal folds) and posterior commissure (or most visible posterior point on the vocal folds) and recording the number of pixels associated with the length. The magnitude, or extent, of lengthwise vocal fold movement during the laryngeal movement cycle associated with vibrato or AMVT was determined by dividing the vocal fold length measure (in pixels) by the standard referent distance (in pixels) (see Figure 9). The extent of lengthwise change was determined using the following equation (6) for each cycle of maximum and minimum movements:

**% vocal fold lengthwise extent = (vocal fold maximum length – vocal fold minimum length) / (vocal fold maximum length + vocal fold minimum length) * 100 (6)**

In the laryngeal oscillation cycle shown in Figure 9, the extent of laryngeal abduction/adduction extent would be:

**Relative VF Lengthwise Extent = (.25 - .24) / (.25+.24) * 100 = 2.0%**

Laryngeal Abduction/Adduction Extent Measures

The interarytenoid distance was measured during maximum and minimum laryngeal cyclic movements to determine changes in abduction and adduction of the vocal folds. Due to the absence, or small number of pixels associated with the glottal width between vocal processes, the interarytenoid distance was used as a surrogate measure to assure adequate sampling distance for analysis. In the absence of a glottis during full approximation of the vocal folds, the measure would yield 0 pixels and would cause errors in the calculation of extent. Thus, interarytenoid distance was determined to reflect changes in glottal width for the purposes of this study.

The interarytenoid distance was measured by drawing a line between the most lateral visible point on the superior surface of the left vocal process and the opposite lateral visible point on the right vocal process (see Figure 9, Part A and B, Image D). The extent of abduction/adduction change was determined using the following equation (7) for each cycle of maximum and minimum movements:

$$\text{\% vocal fold ABDuction / ADDuction extent} = (\text{vocal fold maximum abduction} - \text{vocal fold minimum abduction}) / (\text{vocal fold maximum abduction} + \text{vocal fold minimum abduction}) * 100 \tag{7}$$

In the laryngeal oscillation cycle shown in Figure 9, the extent of laryngeal abduction/adduction extent would be:

**Relative Vocal Fold Abductor/Adductor Extent =**

$$(.14 - .13) / (.14 + .13) * 100 = 3.7\%$$

## Statistical Analysis

The dependent variables for investigation are the average rate and extent of $f_o$ and SPL acquired from acoustic recordings; the average rate and extent of respiratory kinematic signals acquired from movements of the chest wall; and the average rate and extent of laryngeal kinematic images acquired from lengthwise laryngeal movements and abductor/adductor laryngeal movements. Each variable was compared within and across voice modulation conditions, vibrato and AMVT (see Table 5).

Statistical analysis was completed to determine whether hypothesized differences between the extent of SPL and $f_o$ for each location of oscillation (respiratory system versus laryngeal system) occurred. To accomplish this, a mixed effects logistic regression was completed to compare dependent variable outcomes predicted between respiratory kinematic measures and associated acoustic modulation measures (%SPL extent > % $f_o$ extent) and laryngeal imaging kinematic measures and associated acoustic modulation measures (lengthwise oscillation = % $f_o$ extent > %SPL extent; abductor/adductor oscillation = %SPL extent > % $f_o$ extent).

Intrarater reliability was also evaluated using an Intra Class Correlation (ICC) approach including calculation of 95% confidence intervals on the 9 files

Table 5. Intrarater reliability determined using intraclass correlations.

| Dependent Variable | AMVT (N=3) | Vibrato (N = 6) |
|---|---|---|
| Avg $f_o$ Rate (Hz) | 0.882 (-0.001 ~0.997) | 1 (NaN ~ NaN) |
| Avg $f_o$ Extent (%) | 0.994 (0.913 ~1) | 0.999 (0.996 ~ 1) |
| Avg SPL Rate (Hz) | 0.857 (-0.105 ~0.996) | 0.878 (0,44 ~0.982) |
| Avg SPL Extent (%) | 0.807 (-0.262 ~0.995) | 0.986 (0.922 ~0.998) |
| Avg Respiratory Kinematic Rate (Hz) | 1 (NaN ~NaN) | 1 (.61 ~ 1) |
| Avg Respiratory Extent (%) | 1 (NaN ~NaN) | 1 (.61 ~ 1) |
| Avg Laryngeal Rate (Hz) | 0.977 (0.683 ~ 0.999) | 0.723 (0.02 ~ 0.955) |
| Avg vocal fold length Extent (%) | 0.934 (.293 ~0.998) | 0.925 (0.622 ~ 0.989) |
| Avg vocal fold abduction/adduction extent (%) | .489 (-0.692 ~0.983) | 0.723 (0.02 ~0.955) |

randomly selected for repeated measures. The 9 measures were only used for reliability measures and were not included in the final analysis.

## Intrarater Reliability

Intraclass Correlation (ICC) results demonstrated high levels of intrarater reliability levels for all dependent variables except for the average vocal fold abduction/adduction extent (%) measure under the AMVT condition which achieved moderate reliability (i.e., 0.5 – 0.6) (see Table 5). The lower reliability levels for vocal fold abduction/adduction measures under the AMVT condition may relate to the lower number of files analyzed ($n = 3$), or may reflect the greater difficulty determining laryngeal oscillation patterns given significantly slower rates of oscillation that included vertical laryngeal movements.

# RESULTS

## Qualitative Analysis of Results

Tables 6 and 7 provide a summary of the average measures and their standard deviations for each subject under the AVMT and vibrato conditions, respectively. As can be seen, individual singers generally exhibited similar rates of acoustic modulation within each of the singing conditions (AMVT versus vibrato). That is, the AMVT condition was associated with slower acoustic modulation rates for both $f_o$ and SPL (i.e., approximately 2-4 Hz) than for the vibrato condition (i.e., approximately 5-7 Hz). Similarly, laryngeal kinematic rates for vocal fold length change and abduction and adduction of the vocal folds were slower under the AMVT voicing condition than for the vibrato condition. Respiratory kinematic rates were absent under the vibrato condition and present at a similar rate to laryngeal kinematic rates for AMVT.

## Respiratory System Contributions to Acoustic Modulation

It was hypothesized that the AMVT condition would be associated with a predominant oscillation of the chest wall contributing to a greater extent of SPL acoustic modulation compared to the vibrato condition. As shown in Tables 6 and 7, the average respiratory kinematic extent for all subjects during the AVMT condition was measured at 47.5% (SD = 1.2%). For the vibrato condition, respiratory kinematic extent was measured at 0% (SD = 0%). The respiratory

Table 6. AVMT voicing condition descriptive statistical summary for individual subjects.

| MEASURES | SUBJECTS | | | | | | | | | | ALL SUBJECTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | |
| **ACOUSTIC** | | | | | | | | | | | |
| **Avg fo Rate (Hz) (SD)** | 3.8 (0.8) | 2.5 (0) | 2.2 (0.3) | 3.7 (1) | 3.5 (1.3) | 2 (0.9) | 2.2 (0.3) | 3.5 (0.9) | 2.5 (0.5) | 1.7 (1.2) | **2.8 (0.8)*** |
| **Avg fo Extent (%) (SD)** | 6.1 (3.2) | 8.9 (0.2) | 2.8 (1.0) | 1.6 (0.3) | 2.7 (0.9) | 2.8 (0.2) | 1.7 (0.2) | 4.2 (0.4) | 2.6 (0.5) | 2.0 (0.5) | **3.5 (2.3)** |
| **Avg SPL Rate (Hz) (SD)** | 3.5 (0.5) | 2.5 (0) | 2.3 (0.3) | 1.8 (0.3) | 1.5 (0) | 1.5 (0) | 2 (0) | 3 (0) | 2 (0) | 1 (0) | **2.1 (0.7)*** |
| **Avg SPL Extent (%) (SD)** | 28.4 (13.1) | 49.5 (5.4) | 35 (8.9) | 12.6 (6.7) | 32.6 (10.6) | 68.2 (08.7) | 23 (1.3) | 49.2 (1.9) | 28.3 (1.6) | 37.7 (9.9) | **40 (20)*** |
| **RESPIRATORY KINEMATICS** | | | | | | | | | | | |
| **Avg Respiratory Kinematic Rate (Hz) (SD)** | 3.7 (0.3) | 2.5 (0.5) | 2.7 (0.8) | 2 (0) | 1.7 (0.3) | 1.7 (0.3) | 2 (0) | 3 (0) | 2.2 (0.3) | 1.8 (0.6) | **2.3 (0.6)*** |
| **Avg Respiratory Kinematic Extent (%) (SD)** | 46.2 (1.2) | 48.5 (0.4) | 45.7 (1.4) | 48.5 (1.3) | 47 (3) | 48.6 (0.1) | 47.6 (1.1) | 48.4 (1.1) | 48.6 (0.5) | 46.1 (4.7) | **47.5 (1.2)*** |
| **LARYNGEAL KINEMATICS** | | | | | | | | | | | |
| **Avg Laryngeal Kinematic Rate (Hz) (SD)** | 6.7 (1.8) | 4.2 (0.3) | 2.5 (1) | 3.7 (3.2) | 2.3 (1.3) | 2.7 (0.3) | 1.8 (1.6) | 5.2 (1) | 3.3 (0.8) | 1.5 (1.5) | **3.4 (1.6)*** |
| **Avg Vocal Fold Lengthwise Extent (%) (SD)** | 1.8 (0.4) | 2.8 (0.5) | 2.4 (0.5) | 3.1 (2.7) | 2.2 (1.5) | 4.3 (1.5) | 0.9 (1.6) | 3 (1.7) | 10.7 (3.2) | 0.7 (0.8) | **3.2 (2.8)** |
| **Avg Vocal Fold Abduction/Adduction Extent (%) (SD)** | 3.4 (1.5) | 3.3 (1.3) | 4.9 (1.7) | 3 (2.6) | 3 (1.3) | 3.3 (0.7) | 1.4 (2.5) | 7.6 (1.5) | 3.7 (1.6) | 3 (3) | **3.7 (1.6)** |

*Signifies measures that are significantly different between voicing conditions.

Table 7. Vibrato voicing condition descriptive statistical summary for individual subjects.

| MEASURES | SUBJECTS | | | | | | | | | | ALL SUBJECTS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | |
| **ACOUSTIC** | | | | | | | | | | | |
| **Avg fo Rate (Hz) (SD)** | 4.5 (0) | 5 (0) | 6.2 (0.3) | 5 (0) | 5.2 (0.3) | 5.3 (0.3) | 6 (0) | 4.5 (0) | 5.3 (0.3) | 4 (0) | **5.1 (0.7)*** |
| **Avg fo Extent (%) (SD)** | 3.5 (0.2) | 4.8 (0.4) | 4.1 (0.7) | 4.4 (0.3) | 2.2 (0.2) | 3.7 (0.4) | 1.9 (0.1) | 4.7 (0.9) | 3.4 (0.3) | 2.0 (0.4) | **3.5 (1.1)** |
| **Avg SPL Rate (Hz) (SD)** | 4.5 (0) | 4.8 (0.3) | 6.2 (0.3) | 5 (0) | 5 (0.5) | 5.2 (0.3) | 5.8 (0.3) | 4.5 (0) | 5.2 (0.3) | 4 (0) | **5 (0.6)*** |
| **Avg SPL Extent (%) (SD)** | 4.5 (1.6) | 8.9 (0.4) | 19.6 (5.7) | 7.2 (1.0) | 2.8 (0.5) | 6.9 (1.3) | 6.7 (0.3) | 9.1 (3.5) | 12.1 (0.7) | 4.4 (1.4) | **10.0 (0)*** |
| **RESPIRATORY KINEMATICS** | | | | | | | | | | | |
| **Avg Respiratory Kinematic Rate (Hz) (SD)** | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | **0 (0)*** |
| **Avg Respiratory Kinematic Extent (%) (SD)** | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | **0 (0)*** |
| **LARYNGEAL KINEMATICS** | | | | | | | | | | | |
| **Avg Laryngeal Kinematic Rate (Hz) (SD)** | 4.2 (1.9) | 6 (1.3) | 10.2 (2) | 6.3 (0.8) | 6.5 (3) | 7.5 (0) | 10.3 (1.6) | 6.5 (0.5) | 6.3 (1.6) | 4.8 (2.5) | **6.9 (2)*** |
| **Avg Vocal Fold Lengthwise Extent (%) (SD)** | 1.8 (1.2) | 2 (0.2) | 3.3 (1.8) | 6.3 (1.3) | 0.9 (0.1) | 5.4 (1.9) | 1.5 (0.4) | 3.8 (0.5) | 3.7 (0.7) | 2.9 (1.1) | **3.2 (1.7)** |
| **Avg Vocal Fold Abduction/Adduction Extent (%) (SD)** | 3.9 (0.8) | 1.5 (0.2) | 4.7 (0.3) | 4.8 (1.7) | 2.2 (0.9) | 5.9 (1.9) | 3 (0.6) | 6.6 (1.2) | 4.1 (0.1) | 2.8 (0.7) | **3.9 (1.6)** |

*Signifies measures that are significantly different between voicing conditions.

kinematic extent was demonstrated to be significantly greater, on average, under the AMVT condition than for vibrato (*p < .001*). Refer to Figure 10 for a graphical comparison of respiratory kinematic extent across the voicing conditions (i.e., AMVT and vibrato).

The average SPL modulation extent for the AVMT condition was measured at 40% (SD=20%), whereas the average SPL extent for the vibrato condition was 10% (SD=0%). The acoustic measure of SPL extent was also significantly greater under the AMVT condition, on average, than for vibrato ($p = .026$) supporting the hypothesized contribution of the respiratory system to voice modulation. Interestingly, the rate of SPL modulation was also found to significantly differ between voicing conditions. Respiratory oscillation under the AMVT condition was associated with significantly slower rate of SPL modulation than for the vibrato condition ($p < .001$). Refer to Figures 11, 12, and 13 for a graphical comparison of kinematic oscillation rates, SPL modulation extent, and SPL modulation rate, respectively, across voicing conditions (i.e., AMVT and vibrato).

## Phonatory System Contributions to Acoustic Modulation

It was hypothesized that the vibrato condition would be associated with a predominant laryngeal kinematic oscillation, vocal fold lengthwise oscillation, resulting in greater $f_o$ modulation extent compared to the AVMT condition. As shown in Tables 6 and 7, The average vocal fold length extent for the vibrato condition was measured at 3.2% (SD = 1.7%). The average vocal fold length extent for the AVMT condition was measured at 3.6% (SD = 3%). Statistical

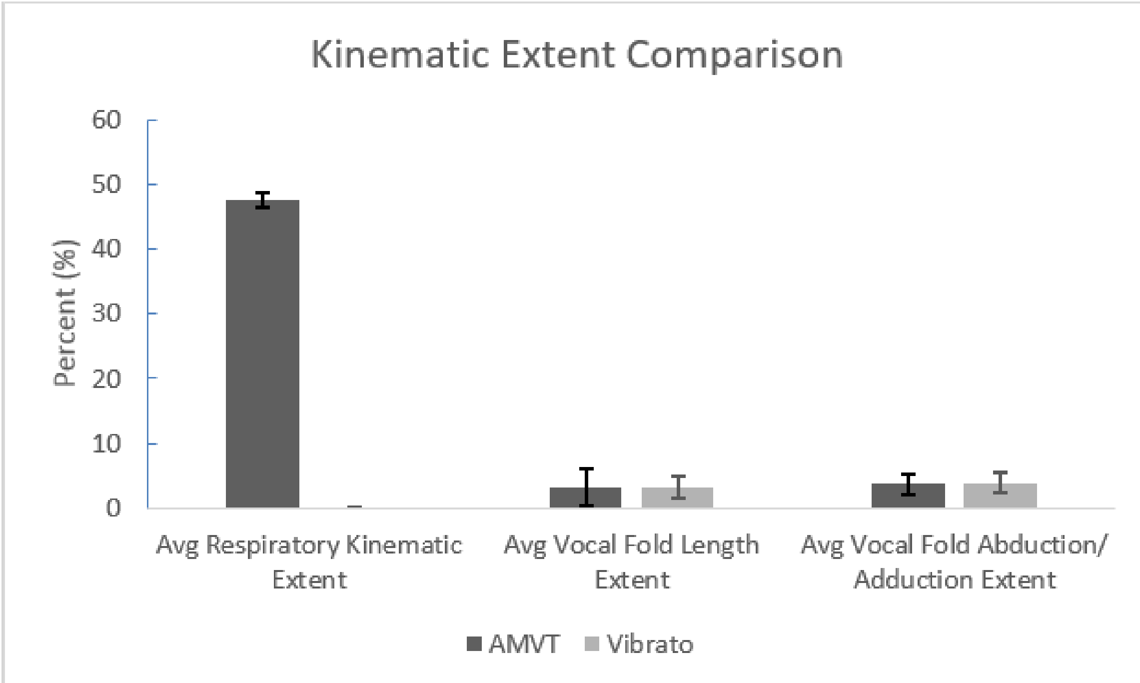



Figure 10. Kinematic extent comparisons between voicing conditions (i.e., AMVT and vibrato)

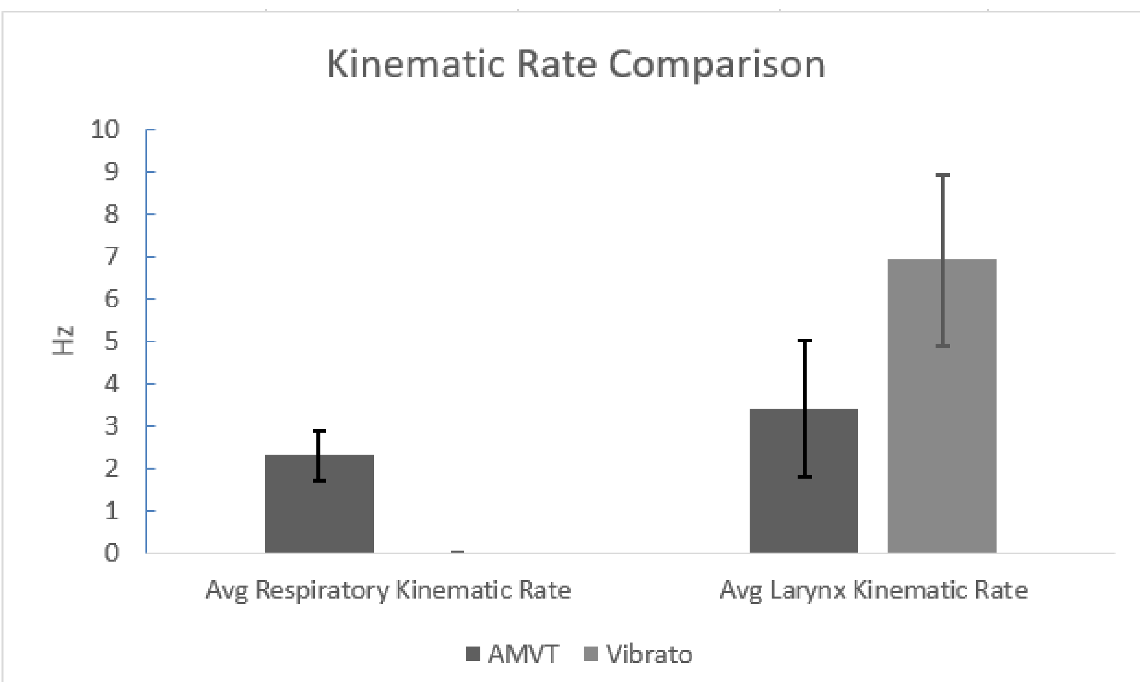



Figure 11. Kinematic extent comparisons between voicing types (i.e., AMVT and vibrato)

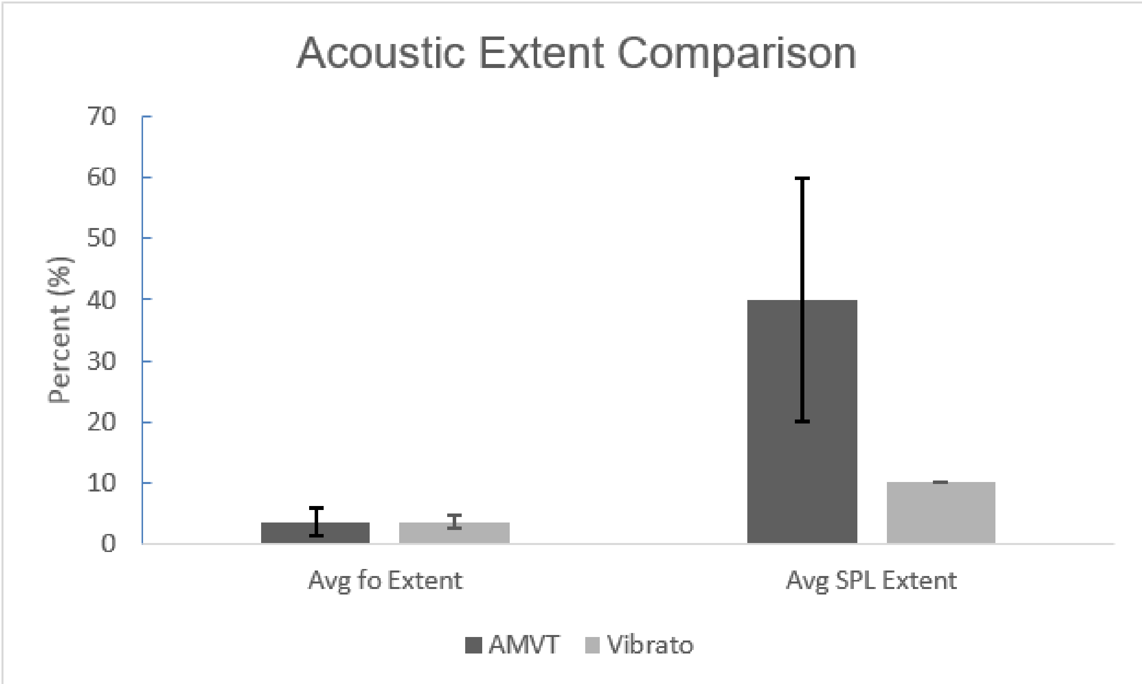



Figure 12. Acoustic extent comparison between voicing conditions (i.e., AMVT and vibrato)

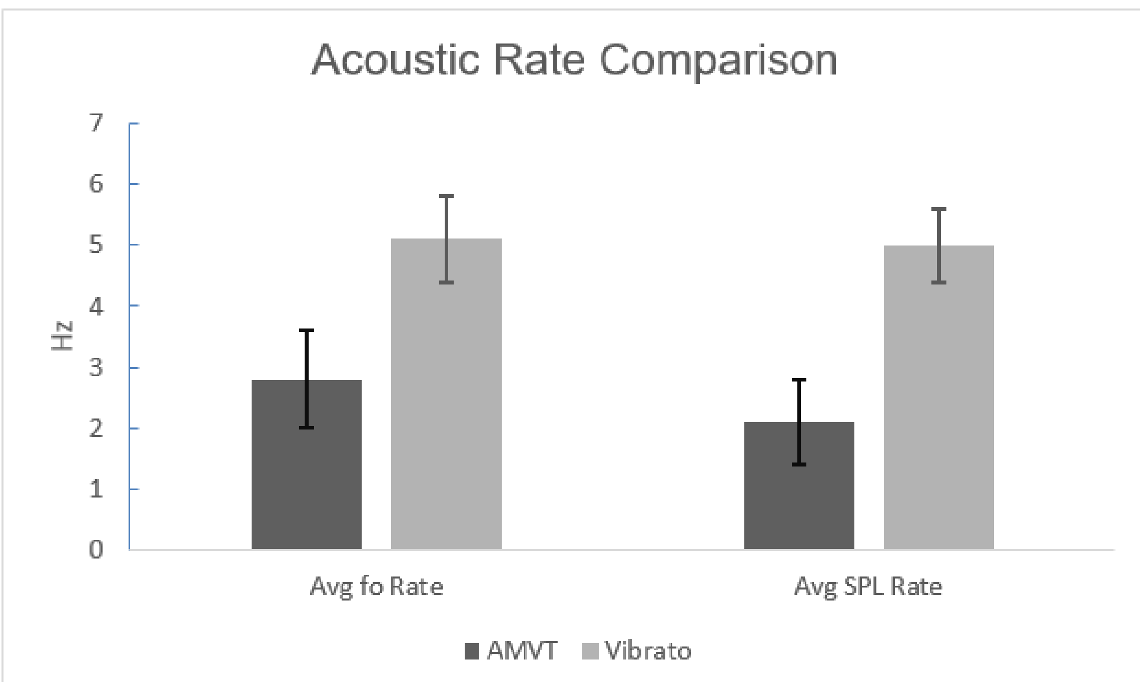



Figure 13. Acoustic rate comparison between voicing conditions (i.e., AMVT and vibrato)

evaluation showed that the laryngeal kinematic extent was not significantly greater under the vibrato condition. Rather, the laryngeal kinematic extent did not significantly differ between the two voice modulation conditions ($p = .95$). Refer to Figure 13 for a graphical comparison of laryngeal kinematic extent across the voicing conditions (i.e., AMVT and vibrato).

The average $f_o$ modulation extent for the vibrato condition was measured at 3.5% (SD = 1.1%). The average $f_o$ modulation extent for the AVMT was 3.5% (SD = 2.3%). The acoustic measure of $f_o$ extent also did not differ significantly under the two voice modulation conditions ($p = .92$) as was hypothesized. However, the rate of $f_o$ modulation was found to significantly differ between voicing conditions demonstrating that laryngeal oscillation under the vibrato condition was a significantly faster rate than for the AVMT condition ($p < .001$). Furthermore, the average laryngeal kinematic rate was significantly higher for the vibrato condition compared to the AVMT condition ($p < .001$). Refer to Figures 12 and 13 for a graphical comparison of $f_o$ modulation extent and rate, respectively, across voicing conditions (i.e., AMVT and vibrato).

## Vocal Tract Movements by Condition

### Vertical Laryngeal Movement

The presence or absence of vertical laryngeal movement was recorded during laryngeal kinematic analysis and observed to demonstrate predominant patterns associated with each voicing condition. During the AVMT condition, 70% of participants demonstrated vertical laryngeal movement in at least 2 of 3 trials or more (67%). In contrast, only 40% of participants demonstrated vertical laryngeal movement in at least 2 of 3 trials in the vibrato condition.

## Pharyngeal Movement

The presence or absence of pharyngeal constriction was recorded during laryngeal kinematic analysis for comparison between voicing conditions. During the AVMT condition, 30% of participants demonstrated pharyngeal movement in at least 2 of 3 trials compared to 60% of participants during the vibrato condition.

# DISCUSSION

The purpose of this study was to test the contribution of respiratory and laryngeal oscillation patterns to acoustic modulation patterns. The conceptual model of vocal tremor developed by Barkmeier-Kraemer and Story (2010) proposed that oscillation of the respiratory system would be reflected by SPL modulation patterns in the acoustic signal. They also proposed that laryngeal oscillation patterns would be associated with acoustic patterns specific to the laryngeal kinematic patterns exhibited. Vocal fold length oscillation was hypothesized to cause $f_o$ extent modulation whereas vocal fold abduction/adduction oscillation would affect interarytenoid distance and be reflected in acoustic SPL extent modulation. The current study investigated voluntary manipulation of laryngeal and respiratory oscillation within trained singers to study associated patterns of acoustic modulation. This was achieved by comparing AVMT and vibrato voicing methods during sustained phonation. AVMT modulates the voice using accented contraction of the respiratory system (Kotby & Fex, 1998). In contrast, vibrato utilizes vocal fold lengthwise oscillation to modulate $f_o$ (Dromey & Smith, 2008; Hsiao, Solomon, Luschei, & Titze, 1994; Sundberg 1994; Titze, et al., 2002).

<u>Respiratory System Contributions to Acoustic Modulation</u>

The results of this study supported the hypothesized contribution of respiratory oscillation to acoustic modulation. The AVMT voicing condition was used to provide respiratory system oscillation during voicing modulation and was shown to predominantly be associated with greater respiratory kinematic oscillation extent and SPL modulation extent. Kotby, Shiromoto, & Hirano (1993), reported that significant SPL modulation occurred associated with abdomino-diaphragmatic contraction during production of the AVMT method of voicing. The current study's outcomes lend support to physiologic models of phonation proposing modulation of SPL associated with respiratory system compression and expansion movements during voicing (Barkmeier-Kraemer & Story, 2010; Farinella, Hixon, Hoit, Story, Jones, 2006; Story, 1995;). The distinct difference between respiratory kinematics and acoustic modulation patterns during the AMVT and vibrato conditions supports prior literature showing that the chest wall portion of the respiratory system does not appear to contribute toward natural vibrato production in trained singers (Pettersen & Westgaard, 2005; Watson, et al., 2012).

The slow respiratory oscillation rate measured during the AVMT condition distinguished respiratory oscillation from laryngeal oscillation in this study. The slower rate of oscillation and acoustic SPL modulation during the AMVT condition compared to the vibrato condition may relate to the larger mass of the respiratory structures and musculature such as the diaphragm, abdominal muscles, and intercostal muscles. In contrast, the laryngeal skeletal framework, structures, and musculature are significantly less massive likely enabling the faster oscillation rates measured for the larynx (Dalvi & Premkumar, 2011).

The findings revolving around the AVMT voicing condition have important clinical implications for clinical evaluation and management of vocal tremor. Individuals with symptoms of vocal tremor exhibiting greater acoustic SPL modulation extent than $f_o$ modulation extent at a rate closer to 3 Hz should be evaluated for respiratory contributions to their vocal tremor. In cases where the respiratory system is the predominant contributor to vocal tremor, consideration regarding optimal medical or behavioral management would be required. For example, vocal tremor is most commonly medically treated by injecting Botox® into the intrinsic laryngeal musculature (i.e., thyroarytenoid, interarytenoid, or posterior cricoarytenoid muscles) (Kendall & Leonard, 1995; Schneider & Deuschl, 2015). This is warranted if the vocal tremor is predominantly caused by tremor within the intrinsic laryngeal muscles. However, vocal tremor caused by the respiratory system and not the laryngeal musculature may not provide optimal results using Botox® injections into the laryngeal musculature (Bove et al., 2006). In addition, behavioral clinical treatment typically involves increased recruitment of respiratory contraction during phonation to offload laryngeal and throat muscle tension. Such a speech treatment approach may be more difficult for individuals to perform if the source of their vocal tremor is from the respiratory system.

Laryngeal Contributions to Acoustic Modulation

Laryngeal oscillation contributions to vocal tremor were hypothesized to result in greater $f_o$ modulation extent acoustically. This was tested in the current study by comparing the correspondence between vocal fold lengthwise and abduction/adduction oscillations during vibrato to modulation of $f_o$ extent. The hypothesized differences between acoustic measures of $f_o$ extent and vocal fold kinematics during AVMT and vibrato were not supported. In contrast, vibrato and AVMT voicing conditions were shown to equally contribute to $f_o$ extent modulation and vocal fold lengthwise and abduction/adduction laryngeal oscillation. Although laryngeal kinematic patterns appeared similar between the AMVT and vibrato conditions, the kinematic rates were significantly different between voicing conditions and closely corresponded with the rate of acoustic modulation for each. That is, the rate of laryngeal kinematic patterns was significantly faster during the vibrato condition than for AMVT. These findings suggest that the laryngeal kinematic patterns measured during the AMVT condition were largely influenced by respiratory system kinematics. This is not entirely surprising given that the larynx is considered to be part of the respiratory system. The utilization of the larynx for voice production cannot be disassociated from its reliance on respiratory pressure and flow patterns for which laryngeal configuration may adjust associated with lung volume levels (Lowell, Barkmeier-Kraemer, Hoit, Story, 2008).

The determination that laryngeal kinematics are similar, but slower during AMVT compared to vibrato demonstrates the reliance of laryngeal configurations on respiratory functions during voice production. In addition, the finding that abduction/adduction vocal fold movements were a component of vibrato is in contrast to prior literature reporting vibrato production associated with the antagonist relationship of the TA and CT muscles (Dromey & Smith, 2008; Hsiao, Solomon, Luschei, & Titze, 1994; Sundberg 1994; and Titze, et al., 2002). The findings in this study suggest that vibrato is produced using a complex interaction between the phonatory, respiratory, and articulatory (i.e., vocal tract) systems.

Another interesting finding of this study was the observation of inferior constrictor muscle activation associated with laryngeal movements during vibrato. This was also not entirely surprising to observe given the suspension of the larynx within the throat by anterior and posterior throat musculature. Thus, observation of counter-contraction of the thyropharyngeus musculature opposite laryngeal vibrato movements is speculated to demonstrate postural stabilization via pharyngeal constrictor muscle activation.

The influence of the respiratory condition in this study (i.e., AVMT) on laryngeal kinematic patterns suggests that laryngeal behaviors are not independent from other speech mechanism structures. This is consistent with prior findings in individuals diagnosed with vocal tremor. For example, a prior study by Lester et al. (2013) tested the contribution of lengthwise vocal fold oscillation to acoustic modulation patterns and did not find support for the predicted contribution of laryngeal oscillation to $f_o$ extent modulation. However, upon expanded acoustic analysis, implication of the vocal tract was found as indicated by formant modulation. Upon further review of the laryngeal imaging recordings, it was discovered that the epilarynx, or laryngeal vestibule oscillatory patterns, were likely affecting formant locations within the vocal tract and affected

SPL extent modulation as predicted by the conceptual framework model. In this study, systematic analysis of laryngeal vocal fold movements in addition to presence/absence of pharyngeal constriction movements documented that laryngeal movements during vibrato (i.e., predominantly laryngeal involvement) were also frequently associated with pharyngeal constriction movements in addition to laryngeal vestibule compression and expansion. These findings suggest that laryngeal oscillations are likely to contribute to alteration of vocal tract configuration requiring co-contraction of vocal tract musculature involved in laryngeal posturing functions. Additional investigation implementing electromyography (EMG) to improve upon prior literature investigating the involvement of supplementary respiratory musculature would help resolve the timing and role of observed vocal tract structure involvement during vibrato production (Finnegan et al., 2003; Tomoda et al., 1987).

In general, the outcomes of this study demonstrate that the vibrato condition shows close correspondence between laryngeal kinematic patterns and respiratory system behaviors. These findings support that speech treatment for vocal tremor that trains improved utilization of the respiratory system may influence laryngeal configurations and muscle contractions associated with laryngeal-based vocal tremor. Importantly, the findings of this study demonstrate significant differences in the rate of vocal tremor associated with laryngeal versus respiratory sources of oscillation as well as acoustic SLP extent modulation patterns. These findings support the proposal of the conceptual model of vocal tremor (Barkmeier-Kraemer and Story, 2010) that the speech structures affected by tremor may be identified by their contributions to the acoustic modulation patterns. However, hypothesized contributions of the larynx to acoustic $f_o$ extent associated with vocal fold lengthwise oscillation was not successfully tested due to linkage between respiratory and laryngeal behaviors during vibrato and AVMT voicing.

Application of Current Findings to Vocal Tremor

The results of this study offer further support for the respiratory contributions to voice modulation as hypothesized by the conceptual model of vocal tremor (Barkmeier-Kraemer & Story, 2010). The current findings showed correspondence between respiratory kinematic patterns and SPL rate and extent of modulation within the AMVT condition. Although respiratory contributions to vocal tremor have not been directly studied, the presence of respiratory structure oscillation in individuals with vocal tremor has been reported in the literature (Tomoda et al., 1987). Future work will need to address similar patterns in those with vocal tremor to confirm similar association of respiratory kinematics and voice modulation.

One problem that has impeded testing of hypothesized laryngeal contributions to voice modulation in vocal tremor is the cooccurrence of oscillation of vocal tract structures with laryngeal oscillations. The current study aimed to isolate laryngeal oscillation through the implementation of vibrato compared to AMVT in trained singers. We hypothesized that laryngeal oscillation would be absent during production of AMVT compared to vibrato. However, the trained singers in this study did not demonstrate differences in vocal fold lengthwise and abduction/adduction kinematic patterns between the AMVT and vibrato conditions as hypothesized. The primary distinction between laryngeal kinematic oscillation patterns in the AMVT and vibrato conditions was the rate of movement. The rate of laryngeal kinematic patterns was significantly slower during the AMVT condition than during the vibrato condition. That is, kinematic pattern rate distinguished between laryngeal oscillation conditions rather than specific SPL or $f_o$ extent of modulation. As such, future work investigating laryngeal kinematic patterns associated with acoustic modulation in those with vocal tremor may benefit from a comparison of acoustic rate patterns to determine the source of oscillation within the speech mechanism. Thus, future research needs to compare and contrast all three sources of tremor (i.e., respiratory, laryngeal, and vocal tract) to further test and refine the conceptual model of vocal tremor.

## Limitations

The current study offered important contributions toward understanding the contributions of laryngeal and respiratory oscillation to SPL and $f_o$ acoustic patterns. Future research on this topic could improve upon the current findings by consideration of methodology limitations of this study.

Laryngeal kinematic measures were limited by the use of nasoendoscopy to analyze the dynamic larynx without a calibrated light grid, or other measurement calibration methods that would have improved upon the accuracy of this study's kinematic measures. That said, the reliability of the laryngeal kinematic measures was highly reliable for all but the abduction/adduction measures specific to the AMVT condition. However, the range of findings for the latter was likely due to the smaller randomly chosen files for analysis that were at least moderately reliable. Future research could be improved by the use of electromyography to study musculature associations with observed movements and incorporation of calibration lighting as this technology improves.

The within-subjects design of this study did not require calibration of SPL for comparison within individuals between two conditions of voicing. SPL calibration signals were recorded; however, the calibration factors caused peak clipping of recorded signals due to the large amplitude signals recorded by singers in this study. Thus, the decision was made to utilize relative SPL. Thus, relative SPL values were recorded and compared within subjects between the two conditions. However, reporting of SPL values in this study requires caution as averaged measures were relative SPL. In future work, calibrated SPL values would enable comparison of SPL between individuals.

Another future consideration would be to include aerodynamic measures of SPL and airflow. Similarly, consideration of laryngeal behaviors associated with lung volume levels would help interpret linked laryngeal and respiratory behaviors during vibrato and AVMT conditions. It is possible that laryngeal oscillation patterns vary between voicing initiation at higher lung volumes compared to voicing toward the end of voicing (Lowell et al., 2008). Such factors may be important to study associated with structural kinematic behaviors to elucidate further the role of the larynx relative to respiratory and vocal tract voice production conditions.

Finally, generalization of the findings of this study to the larger population of singers will require increased numbers of participants in future work. However, the robust outcomes of this study would be expected to be supported in future larger studies.

## Conclusion

The purpose of this study was to test the conceptual model of vocal tremor developed by Barkmeier-Kraemer and Story, 2010 by linking respiratory and laryngeal kinematic oscillations to acoustic modulation patterns during AVMT and vibrato conditions. Specifically, respiratory oscillation during AVMT was hypothesized to correspond with the acoustic extent of SPL modulation whereas lengthwise oscillation of the vocal folds during vibrato voicing was hypothesized to correspond with the acoustic extent of $f_o$ modulation. The hypothesized contributions of the respiratory system to SPL modulation were confirmed. However, the hypothesized contributions of the phonatory system to $f_o$ modulation were not supported. Laryngeal kinematic patterns during vibrato and AVMT appeared similar although vibrato oscillations occurred at a significantly higher rate than measured during AVMT. The linkage between the larynx and respiratory kinematic patterns suggest that the laryngeal movements were unable to be voluntarily isolated. These findings offer important information about laryngeal and respiratory physiology that may be further investigated for utility in the clinical evaluation and treatment of individuals with vocal tremor.

# APPENDIX

# QUESTIONNAIRE FOR SINGING PARTICIPANTS

Questionnaire for Singing Participants

Please answer the questionnaire completely.

Age: _________ Gender: _____________

1) How many years of vocal training have you had?

____________________________________________________________

2) In what genre(s) do you feel most comfortable singing?

____________________________________________________________

3) How would you describe your current singing voice condition (e.g., in-shape, sing often, been a while since I've sung, etc.)?

____________________________________________________________

4) Do you use vibrato while you sing?

____________________________________________________________

   a. If you answered yes to #4, how often do you use vibrato while singing (e.g., all the time, at the end of phrases, etc.)?

   ______________________________________________________

   b. If you answered yes to #4, have you experienced or are you currently experiencing any problems with your vibrato? ______

   c. If you answered yes to #4, do you vary your vibrato production across genres? ______

      i. If so, how?

      ________________________________________________

      ________________________________________________

5) Are you currently experiencing any voice problems? If so, describe:

____________________________________________________________

____________________________________________________________

REFERENCES


Ackermann, H., & Ziegler, W. (1991). Cerebellar voice tremor: an acoustic analysis. *Journal of Neurology, Neurosurgery & Psychiatry, 54*(1), 74-76.

Adler, C. H., Bansberg, S. F., Hentz, J. G., Ramig, L. O., Buder, E. H., Witt, K., Edwards, B. W., Krein-Jones, K., Caviness, J. N., (2004). Botulinum toxin type A for treating voice tremor. *Archives of Neurology, 61*(9), 1416-1420.

Anand, S., Shrivastav, R., Wingate, J. M., & Chheda, N. N. (2012). An acoustic-perceptual study of vocal tremor. *Journal of Voice, 26*(6), 811-817.

Anand, S., Wingate, J. M., Smith, B., & Shrivastav, R. (2012). Acoustic parameters critical for an appropriate vibrato. *Journal of Voice, 26*(6), 819-825.

Barkmeier-Kraemer, J., Lato, K., & Wiley, K. (2011). Development of a speech treatment program for a client with essential vocal tremor. *Seminars in Speech and Language*, *32*(1), 43-57.

Barkmeier-Kraemer, J., & Story, B. (2010). Conceptual and clinical updates on vocal tremor. *ASHA Leader, 15*(14), 16-19.

Boersma, Paul & Weenink, David (2015). Praat: doing phonetics by computer [Computer program]. Version 5.4.09, Retrieved 2 June 2015 from http://www.praat.org/

Bové, M., Daamen, N., Rosen, C., Wang, C.-C., Sulica, L., & Gartner-Schmidt, J. (2006). Development and validation of the vocal tremor scoring system. *The Laryngoscope, 116*(9), 1662-1667.

Brown, JR & Simonson, J (1963). Organic voice tremor. A tremor of phonation. *Neurology*, *13*, 520-525.

Cohen, S. M., Jacobson, B. H., Garrett, C. G., Noordzij, J. P., Stewart, M. G., Attia, A., Cleveland, T. F. (2007). Creation and validation of the singing voice handicap index. *Annals of Otology, Rhinology & Laryngology, 116*(6), 402-406.

Dalvi, A., & Premkumar, A. (2011). Tremor: etiology, phenomenology, and clinical features. *Disease-a-Month, 57*(3), 109-126.

Dromey, C., & Smith, M. E. (2008). Vocal tremor and vibrato in the same person: acoustic and electromyographic differences. *Journal of Voice, 22*(5), 541-545.

Dromey, C., Warrick, P., & Irish, J. (2002). The influence of pitch and loudness changes on the acoustics of vocal tremor. *Journal of Speech, Language & Hearing Research, 45*(5), 879.

Farinella K. A., Hixon T. J., Hoit J. D., Story B. H., Jones P. A. (2006). Listener perception of respiratory-induced voice tremor. *American Journal of Speech Language Pathology*, *15*(1):72-84.

Finnegan, E. M., Luschei, E. S., Barkmeier, J. M., & Hoffman, H. T. (2003). Synchrony of laryngeal muscle activity in persons with vocal tremor. *Archives of Otolaryngology–Head & Neck Surgery, 129*(3), 313-318.

Gamboa, J., Jiménez-Jiménez, F. J., Nieto, A., Cobeta, I., Vegas, A., Ortí-Pareja, M., García-Albea, E. (1998). Acoustic voice analysis in patients with essential tremor. *Journal of Voice, 12*(4), 444-452.

Gurey, L., Sinclair C., & Blitzer, A. (2013). A new paradigm for the management of essential vocal tremor with botulinum toxin. *Laryngoscope, 123*(10), 2497-2501.

Guzman, M. A., Dowdall, J., Rubin, A. D., Maki, A., Levin, S., Mayerhoff, R., & Jackson-Menaldi, M. C. (2012). Influence of emotional expression, loudness, and gender on the acoustic parameters of vibrato in classical singers. *Journal of Voice, 26*(5), 675.

Howes, P., Callaghan, J., Davis, P., Kenny, D., & Thorpe, W. (2004). The relationship between measured vibrato characteristics and perception in Western operatic singing. *Journal of Voice, 18*(2), 216-230.

Hsiao, T.-Y., Solomon, N. P., Luschei, E. S., & Titze, I. R. (1994). Modulation of fundamental frequency by laryngeal muscles during vibrato. *Journal of Voice, 8*(3), 224-229.

Jacobson, B. H., Johnson, A., Grywalski, C., Silbergleit, A., Jacobson, G., Benninger, M. S., & Newman, C. W. (1997). The voice handicap index (vhi) development and validation. *American Journal of Speech-Language Pathology, 6*(3), 66-70.

Jiang, J., Lin, E., & Hanson, D. G. (2000). Acoustic and Airflow Spectral Analysis of Voice Tremor. *Journal of Speech, Language & Hearing Research, 43*(1), 191.

Kendall, K. A., & Leonard, R. J. (2011). Interarytenoid muscle botox injection for treatment of adductor spasmodic dysphonia with vocal tremor. *Journal of Voice*, *25*(1), 114-119.

Kirkpatrick, A. (2008). Teaching methods for correcting problematic vibratos: using sustained dynamic exercises to discover and foster healthy vibrato. *Journal of Singing, 64*(5), 551-556.

Kotby, M., & Fex, B. (1998). the accent method: behavior readjustment voice therapy. *Logopedics Phoniatrics Vocology, 23*(1), 39-43.

Kotby, M., Shiromoto, O., & Hirano, M. (1993). The accent method of voice therapy: Effect of accentuations on FO, SPL, and airflow. *Journal of Voice, 7*(4), 319-325.

Lederle, A., Barkmeier-Kraemer, J., & Finnegan, E. (2012). Perception of vocal tremor during sustained phonation compared with sentence context. *Journal of Voice, 26*(5), 668-669.

Lester, R. A., Barkmeier-Kraemer, J., & Story, B. H. (2013). Physiologic and acoustic patterns of essential vocal tremor. *Journal of Voice, 27*(4), 422-432.

Louis, E. D., & Machado, D. G. (2015). Tremor-related quality of life: A comparison of essential tremor vs. Parkinson's disease patients. *Parkinsonism & Related Disorders, 21*(7), 729-735.

Lowell S. Y., Barkmeier-Kraemer J. M., Hoit J. D., Story B. H. (2008). Respiratory and laryngeal function during spontaneous speaking in teachers with voice disorders. *Journal of Speech, Language, and Hearing Research*, *51*(2):333-49.

Lundy, D. S., Roy, S., Xue, J. W., Casiano, R. R., & Jassir, D. (2004). Spastic/spasmodic vs. tremulous vocal quality: motor speech profile analysis. *Journal of Voice, 18*(1), 146-152.

Pettersen, V., & Westgaard, R. H. (2005). The activity patterns of neck muscles in professional classical singing. *Journal of Voice, 19*(2), 238-251.

Prame, E. (1994). Measurements of the vibrato rate of ten singers. *The Journal of the Acoustical Society of America, 96*(4), 1979-1984.

Ramig, L. A., & Shipp, T. (1987). Comparative measures of vocal tremor and vocal vibrato. *Journal of Voice, 1*(2), 162-167.

Rasband, W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, Retrieved from http://imagej.nih.gov/ij/, 2015

Schneider, S. A., & Deuschl, G. (2015). Medical and surgical treatment of tremors. *Neurologic Clinics, 33*, 57-75.

Seashore, C. E. (1931). The natural history of the vibrato. *Proceedings of the National Academy of Sciences of the United States of America, 17*(12), 623-626.

Story, B. H. (1995). *Physiologically-based speech simulation using and enhanced wave-reflection model of the vocal tract.* (Unpublished doctoral dissertation). University of Iowa, Iowa City, IA.

Sulica, L., & Louis, E. D. (2010). Clinical characteristics of essential voice tremor: A study of 34 cases. *The Laryngoscope, 120*(3), 516-528.

Sundberg, J. (1994). Acoustic and psychoacoustic aspects of vocal vibrato. *STL-QPSR, 35*(2-3), 045-068.

Taha, J. M., Janszen, M. A., & Favre, J. (1999). Thalamic deep brain stimulation for the treatment of  head, voice, and bilateral limb tremor. *Journal of Neurosurgery, 91*(1), 68-72.

Titze, I. R., Story, B., Smith, M., & Long, R. (2002). A reflex resonance model of vocal vibrato. *The Journal of the Acoustical Society of America, 111*(5), 2272-2282.

Tomoda, H., Shibasaki, H., Kuroda, Y., & Shin, T. (1987). Voice tremor: dysregulation of voluntary expiratory muscles. *Neurology, 37*(1), 117-122.

Warrick, P., Dromey, C., Irish, J., Durkin, L., Pakiam, A., Lang, A. (2000). Botulinum toxin for essential tremor of the voice with multiple anatomical sites of tremor: a crossover design study of unilateral versus bilateral injection. *Laryngoscope, 110*(8), 1366-74.

Watson, A. H. D., Williams, C., & James, B. V. (2012). Activity patterns in latissimus dorsi and sternocleidomastoid in classical singers. *Journal of Voice, 26*(3), 95-105.

Wolraich, D., Marchis-Crisan, C.V., Redding, N., Khella, S.L., & Mirza, N. (2010). Laryngeal tremor: co-occurrence with other movement disorders. *Otorhinolaryngology*, *72,* 291–294.